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VARIABLE CYCLE ENGINE EVALUATIONS FOR SUPERSONIC V/STOL FIGHTER--ETC(U)
APR 78 J E CUPSTID, D G GLENNIE N00140-75-C-0034

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VARIABLE CYCLE ENGINE EVALUATIONS FOR SUPERSONIC V/STOL FIGHTERS

MANAGEMENT SUMMARY REPORT

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Variable cycle engines (VCE) have been evaluated using advanced V/STOL fighter designs. The VCE payoffs were assessed in terms of total weapon system cost effectiveness and results indicate that they offer potential benefits in supersonic V/STOL fighters.

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A systematic engine/airframe evaluation procedure was developed and used to assess interactions for advanced engine concepts in L + L/C aircraft designs. The evaluation procedure provides a rapid and inexpensive technique for evaluating engine concepts considering a large matrix of engine and airframe design and sizing variables. The procedure was used to establish a parametric data base using both fixed cycle turbofans and variable geometry turbine turbojets. Specific engine/airframe designs were then selected for detailed comparisons.

Engine/airframe design evaluations were also conducted using a variable cycle turbofan engine capable of being used with both L + L/C and L/C aircraft. These aircraft designs were compared to the fixed cycle turbofan and variable geometry turbine turbojet aircraft designs in terms of TOGW, performance, life cycle cost and operational flexibility.

FOREWORD

This report was prepared by the McDonnell Aircraft Company (MCAIR) a division of the McDonnell Douglas Corporation, St. Louis, Missouri for the Naval Air Propulsion Center, Trenton, New Jersey. This study was performed under Navy Contract N00140-75-C-0034, "Variable Cycle Engine Selection Program" from June 1975 through November 1977. Program direction was provided by Mr. J.R. Facey, Program Manager, and Mr. Paul Piscopo of the Naval Air Propulsion Center and Mr. John Cyrus of the Naval Air Development Center. The program was under the direction of Mr. R.E. Martens, MCAIR Program Manager and Mr. F.C. Glaser, Technical Director.

The authors of this report, J.E. Cupstid and D.G. Glennie, are indebted to R.L. Crossen, B.T. Phelps, and R.W. Holzwarth for their technical assistance. The authors are also indebted to C.W. Miller, H.H. Ostroff, H. Sams, and J.M. Sinnett of MCAIR, who, in their supervisory positions made valuable contributions throughout the program.

SUMMARY

The propulsion system design and its integration with the airframe are major considerations in defining a high performance V/STOL fighter aircraft. The propulsion system must provide thrust in excess of aircraft weight for vertical takeoff, operate efficiently during conventional flight, and integrate with an aerodynamically efficient airframe configuration. Variable cycle engines (VCE), incorporating multiple flow paths and/or variable turbine geometry, offer a potential for achieving these objectives with substantially less cost and weight penalties than encountered with fixed cycle engines. The NAPC funded "Variable Cycle Engine Selection Program" (Contract N00140-75-C-0034) was specifically directed toward evaluating VCE concepts for advanced, supersonic Navy V/STOL fighters. This report presents a summary of the results obtained in this three phase program. References 1 and 2 present a more detailed technical discussion of the Phase I results and Phases II and III are reported in Reference 3.

In Phase I, a preliminary screening of VCE concepts, provided by Detroit Diesel Allison and General Electric, was conducted using takeoff gross weight (TOGW) sensitivities. The results showed a potential VCE payoff of 8% to 13% in TOGW when compared to fixed cycle engines. A GE modulating bypass turbofan concept was selected for more detailed evaluation in Phases II and III. The GE engine work for this program was conducted under Contract N00140-75-C-2034 and is reported in the GE Final Summary Report.

A key Phase II activity was the modification of an engine/airframe evaluation procedure, Reference 4, developed for the Air Force by MCAIR. The Air Force procedure was developed for conventional take-off and landing aircraft and was modified in this program to permit evaluation of V/STOL aircraft. This V/STOL Fighter Design Evaluating Procedure permits calculation of the size, cost, mission and performance characteristics of a systematically selected matrix of lift + lift/cruise (L + L/C) V/STOL fighter aircraft designs. Mathematical relationships are defined to relate aircraft TOGW, cost, mission and performance characteristics to engine and airframe design variables. Finally, an optimization procedure is used to select aircraft designs for specified mission and performance requirements. The optimization pay-off functions can be TOGW, life cycle cost, or aircraft capability parameters.

The V/STOL Fighter Design Evaluation Procedure permits simultaneous consideration of up to eleven engine/airframe design variables and up to seventeen mission and performance requirements. The results permit identification and evaluation of the effects of propulsion system/airframe interactions on system characteristics. In addition, the effects of aircraft mission and performance requirements on aircraft size, cost and operational flexibility can be readily determined.

The Evaluation Procedure was used in Phase II to develop a data base of aircraft characteristics, using GE fixed cycle turbofan engines (FCE-TF), and to optimize an aircraft design to provide a basis for subsequent VCE payoff evaluations.

In Phase III, a data base of aircraft characteristics was developed using GE variable geometry turbine turbojet (VGTTJ) engines. These data were used to assess the effects of aircraft mission and performance requirements on aircraft design for comparison with the FCE-TF aircraft. The VGTTJ aircraft provided reductions of 11% and 9% in TOGW and life cycle cost respectively when sized to achieve representative Navy mission and performance requirements. In addition, the data bases have been transmitted to GE and the Naval Air Development Center for use in continuing trade-off studies.

In Phases II and III, aircraft design, performance, and cost analyses were also conducted using versions of the modulating bypass turbofan selected in Phase I. This engine can provide airflow to a remotely located augmentor during VTO and thereby potentially eliminate the need for separate lift engines. Consequently, significantly reduced powered lift system development costs were anticipated. Using the Remote Augmentor Lift System/VCE concept, total system life cycle cost was estimated to be 4.0% below that of a L + L/C FCE-TF aircraft. However, when sized to provide equivalent combat performance, life cycle cost of the RALS/VCE aircraft system was estimated to be 10% below that of the VGTTJ L + L/C aircraft.

L + L/C designs, using the modulating bypass turbofan VCE without the RALS feature, were evaluated and showed a 9% TOGW payoff relative to the FCE-TF aircraft. As a result, the VCE powered L + L/C aircraft life cycle costs were competitive with the FCE-TF aircraft.

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LIST OF ILLUSTRATIONS

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SYMBOLS AND ACRONYMS

Symbol	Definition
AR	Wing Aspect Ratio
A/B	Afterburner
BPR	Engine Bypass Ratio
C_D	Drag Coefficient
C_{fg}	Nozzle Thrust Coefficient
C.G.	Center of Gravity
CPR	Compressor Pressure Ratio
DDA	Detroit Diesel Allison
DLE	Direct Lift Engine
DLI	Deck Launched Intercept
EM	Energy Maneuverability Flight Condition
E_s	Energy Expenditure - ft
F_{N_V}	Vertical Net Thrust - lb
FCE	Fixed Cycle Engine
F.E.	Fighter Escort
FPR	Engine Fan Pressure Ratio
GE	General Electric
INST	Installed
IOC	Initial Operational Capability
LCC	Life Cycle Cost
LP	Low Pressure
L + L/C	Lift Engine + Lift/Cruise Engine
M.A.C.	Mean Aerodynamic Chord - in
M_o	Mach Number

SYMBOLS AND ACRONYMS (Continued)

Symbol	Definition
M&H	Mach & Altitude
η_z, N_{z_s}	Normal Load Factor - g
NM	Nautical Miles
NPF, F_{np}	Net Propulsive Force - lb
OPR	Engine Overall Compression Ratio
O&S	Operation and Support
P_s	Specific Excess Power - ft/sec
PEX	Nozzle Exit Static Pressure Ratio
P_∞	Freestream Static Pressure
q	Dynamic Pressure - lb/ft^2
RDT&E	Research Development Test and Evaluation
RPM	Revolutions per Minute
Λ(LAM)	Wing Sweep
SFC	Engine Specific Fuel Consumption - lb/hr/lb
SLS	Sea Level Static
SSS	Subsonic Surface Surveillance
STO	Short Takeoff
T_{EXIT}	Nozzle Exit Temperature - °F
TF	Turbofan
TIT	Engine Turbine Inlet Temperature - °R
TOGW	Takeoff Gross Weight - lb
T/W	Thrust/Weight
VCE	Variable Cycle Engine
VGTTJ	Variable Geometry Turbine Turbojet
VL	Vertical Landing

SYMBOLS AND ACRONYMS (Continued)

Symbol	Definition
VTO	Vertical Takeoff
$\frac{W\sqrt{\theta}}{\delta}$	Engine Corrected Airflow - lb/sec
W_F	Engine Fuel Flow - lb/hr
WOD	Wind-Over-Deck - knots
W/S, WOS	Aircraft Wing Loading, lb/ft^2
ΔTAMB	Engine Airflow Scheduling Variable - deg's
$\%N_2$	Percent Max Compressor Speed

Acronyms

ADEN	Augmented Deflector Exhaust Nozzle
CADE	Computer Aided Design Evaluation Computer Program
CAP	Combat Air Patrol
CTOL	Conventional Takeoff and Landing
RALS	Remote Augmentor Lift System
SEARCH	Optimization Computer Program
STOVL	Short Takeoff/Vertical Landing
SURFIT	Surface Fit Computer Program
V/STOL	Vertical/Short Takeoff and Landing
VABI	Variable Area Bypass Injector

1. INTRODUCTION

The inherent operational flexibility of variable cycle engines may provide significant benefits in supersonic V/STOL fighters. The combination of powered lift and forward flight performance requirements of supersonic V/STOL fighters necessitate extensive compromises in the design and scheduling of fixed cycle engines. These compromises have resulted in high take-off gross weights and relatively poor payload and range performance in many designs when compared to conventional supersonic fighters. Variable cycle engines can potentially reduce the compromises necessary with fixed cycle engines with attendant improvements in weight and performance.

During the past several years, a variety of VCE concepts have been identified by the engine companies for CTOL aircraft applications. Such engines are highly adaptable to achieving increased thrust, reduced fuel consumption, or reduced noise at desired flight conditions. However, these engines generally exhibit penalties in weight, size and cost. Consequently, selection of the specific engine design and operational characteristics for advanced aircraft must be based upon systematic definition and evaluation of the impact of these engine characteristics on the total weapon system.

Systematic engine evaluation procedures were developed and demonstrated for the Air Force in the Reference 4 program. These procedures account for the interactions between requirements for CTOL aircraft. They were directly applicable to similar evaluations of V/STOL fighters with modification required to only selected program elements.

Eight V/STOL VCE concepts, defined by Detroit Diesel Allison and General Electric, were postulated to meet the needs of supersonic V/STOL propulsion systems. Both axisymmetric and 2-D V/STOL nozzle concepts were included. A preliminary screening was conducted to estimate the potential impact of each VCE on V/STOL fighter TOGW and to select the most promising concept for more detailed evaluations. TOGW payoffs of 8% to 13% were obtained when compared to fixed cycle engine V/STOL fighters, References 1 and 2. As a result of this preliminary screening, NAPC selected a General Electric modulating bypass turbofan concept for detailed evaluation in Phases II and III. This concept provides the versatility to be used in either L + L/C or L/C V/STOL fighters. In addition, the General Electric 2-D Augmented Deflector Exhaust Nozzle (ADEN) was selected by NAPC for the Phase II and III evaluations. This nozzle provides the capability to augment in the vectored thrust operating mode.

MCAIR's VCE evaluations are discussed in the following sections. The evaluation approach is described in Section 2. Parametric evaluation results, using fixed cycle turbofan and variable geometry turbine turbojet engines are presented in Section 3. The modulating bypass turbofan engine evaluation

results are presented in Section 4. VCE payoffs are identified in Section 5 and conclusions and recommendations are presented in Section 6.

2. APPROACH

Potential payoffs of advanced engine concepts for supersonic V/STOL aircraft must be assessed in terms of such system characteristics as takeoff gross weight (TOGW), life cycle cost, and operational flexibility. The impact of mission and performance requirements must also be considered in conducting these assessments. Phase I of this program consisted of a preliminary screening of variable cycle engine concepts and selection of the most promising for more detailed evaluations in Phases II and III. The results of Phase I are presented in References 1 and 2. The Phase II and III engine evaluation approach is illustrated in Figure 1. Parametric engine/airframe evaluations were conducted to establish a data base using advanced fixed cycle turbofan (FCE-TF) and variable geometry turbine turbojet (VGTTJ) engines. This data base was used to select a reference FCE-TF aircraft design and a VGTTJ aircraft design. The VGTTJ represented a special class of variable cycle engines having an intermediate level of flexibility between the FCE-TF and the VCE's evaluated in Phase I. Evaluations of a variable cycle engine turbofan, VCE-TF, selected in Phase I, were also conducted. However, due to the preliminary design status of the engine, parametric descriptions of the size, weight, performance and cost characteristics of this engine were not available and the evaluations were conducted using point design integration layout and performance analysis procedures.

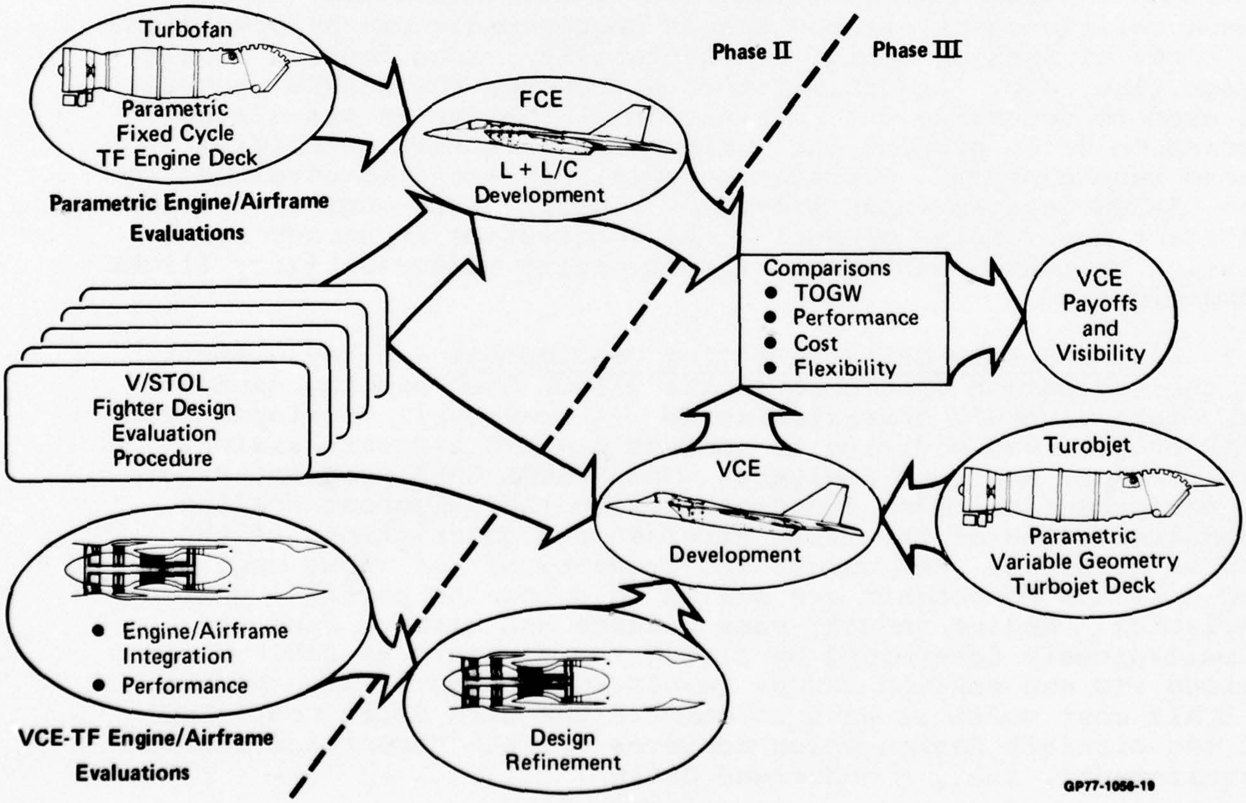


FIGURE 1
PHASE II AND III APPROACH

The following sections present a brief description of the key activities, analysis procedures, and technical guidelines used to conduct the Phase II and III evaluations. Section 2.1 describes the evaluation procedure used to develop parametric relationships between V/STOL weapon system characteristics and pertinent engine, airframe, and requirement parameters. The use of the procedure to develop system characteristics for parametric matrices of fixed cycle turbofan and variable geometry turbine turbojet engines is described in Section 2.2. Finally, Section 2.3 describes the procedures used to evaluate the VCE-TF engine concept.

2.1 V/STOL Fighter Design Evaluation Procedure - Parametric aircraft system characteristics are computed and related to pertinent engine, airframe, and requirement parameters using the V/STOL Fighter Design Evaluation Procedure. As illustrated in Figure 2, an initial engine and airframe design and the missions to be considered are required inputs to the procedure. Parametric matrices of aircraft designs are defined by systematically varying engine and airframe design parameters and aircraft thrust and fuel sizing variables. The size, performance, and cost of each aircraft in the matrix are calculated using the Computer Aided Design Evaluation (CADE) program. Correlation equations are then developed which describe the relationships between each aircraft size, performance, and cost parameter computed by CADE and the design and sizing variables. Using these relationships, weapon system requirements can be specified in terms of mission radii, maneuverability, load factor, acceleration time, etc. An optimization procedure, the SEARCH program, is used to determine the combination of the design and sizing variables which produce the minimum TOGW aircraft satisfying those requirements. Correlation equations are also developed for the SEARCH program which provide visibility into engine/airframe interactions, engine operating characteristics at steady state mission segments, and engine thrust sizing maneuverability flight conditions.

2.2 Weapon System Characteristics Development - A key element of the evaluation procedure is the V/STOL CADE program used to calculate aircraft characteristics. A previously developed CTOL CADE program was modified to conduct L + L/C aircraft sizing, performance, and cost analyses. The V/STOL CADE program, Figure 3, performs five major functions, using the component scaling characteristics of the input aircraft and descriptions of the V/STOL missions. The weight and geometry of the input engine and airframe components are scaled to determine physical characteristics. Engine thrust, mass balance and mission fuel are simultaneously determined by sizing the aircraft to achieve required VTO and mission thrust levels and design mission radius. A MCAIR cost model is used to compute the Life Cycle Cost (LCC) of the aircraft design which achieves all the thrust and radius requirements, i.e., a converged design.

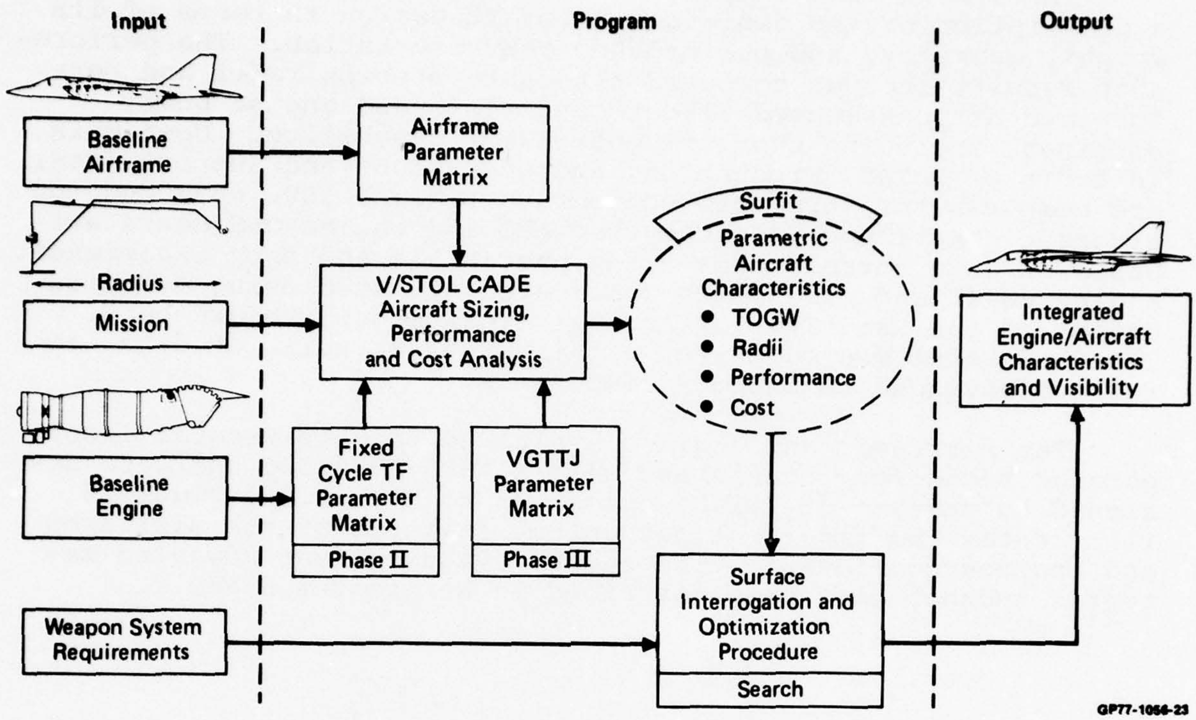


FIGURE 2
V/STOL FIGHTER DESIGN EVALUATION PROCEDURE

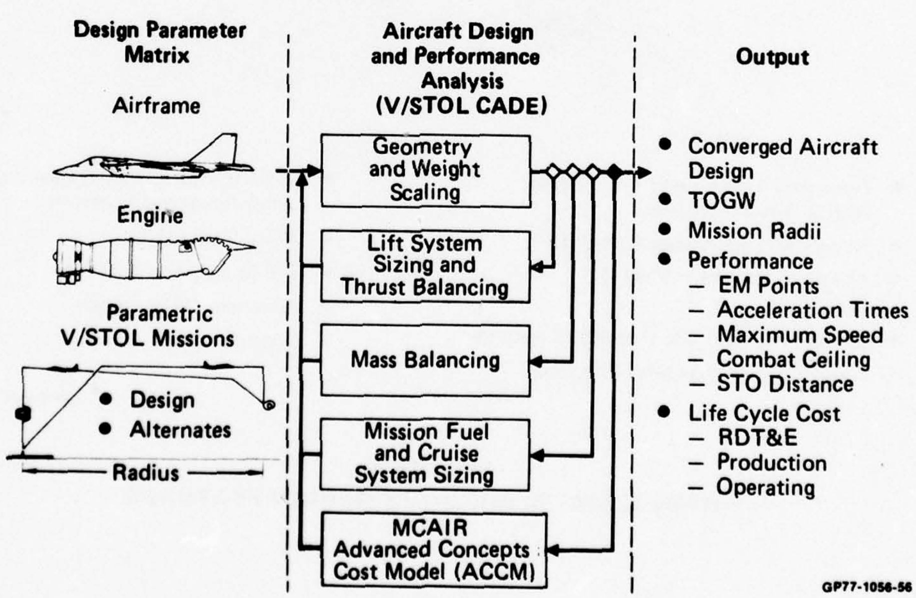
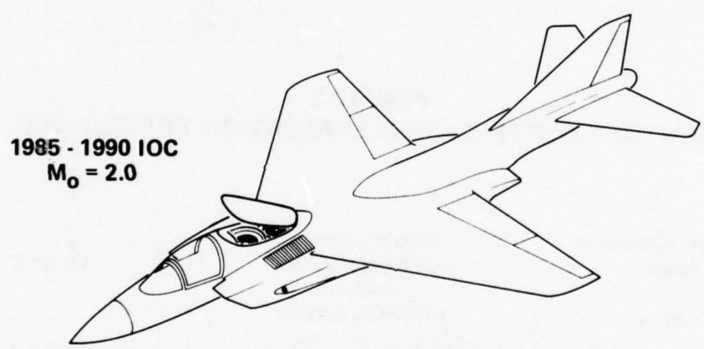


FIGURE 3
DETERMINATION OF PARAMETRIC AIRCRAFT DESIGN CHARACTERISTICS (CADE)

The V/STOL CADE output, as indicated in Figure 3, includes a description of the converged aircraft design in terms of its weight, geometry, and performance characteristics. The performance results include computed alternate mission radii and performance at preselected flight conditions and engine power settings, including short takeoff (STO) capability. Cost data in terms of RDT&E, Production, and Operations and Support (O&S) are computed for three production quantities, 300, 600, and 900 aircraft. Airframe and subsystem LCC and engine O&S costs are based on data correlations using past MCAIR and Navy experience. Engine RDT&E and production costs are estimated using a modification of the Rand Time of Arrival (TOA) Model, Reference 5. The Rand Model was modified in this program, using GE data, to reflect advanced technology components.

The airframes and engines evaluated in this program incorporated technology consistent with a 1985-1990 IOC and were designed to operate at flight speeds up to Mach 2.0. Figure 4 illustrates the important technology features of the airframes and engines considered. The radar, avionics, and advanced material technologies were described in References 6 and 7.



- Advanced Technology L/C Engines with 2-D Aden Nozzles
- Advanced Technology Lift Engines
- Auxiliary Inlets for V/STOL Operation
- 30 mm Gun and 500 Rounds of Ammo
- Air/Air and Air/Ground Weapons
- 15% Structural Weight Savings by Using Advanced Materials
- 24 in. Radar Dish
- 925 lb Avionics Package
- Advanced Wing Design
- Decamber Flap

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FIGURE 4
PHASE II AND III AIRCRAFT DESIGN FEATURES

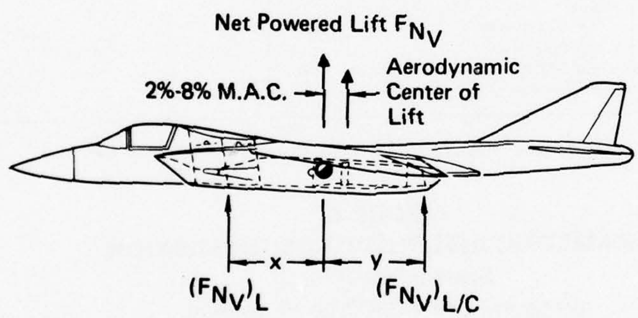
Engine and airframe integration is based on four major design considerations. These considerations are illustrated in Figure 5 and discussed below:

(1) Powered lift system sizing to provide a net lift/TOGW ratio of 1.05, accounting for lift losses due to non-standard day (90°F) operation, reingestion, ground effects, control margin and primary/auxiliary inlet performance.

(2) Powered lift thrust balancing is accomplished by positioning the lift engines forward of the aircraft C.G. to balance the moment produced by the lift/cruise engines. Lift/cruise engines are sized to meet specified aircraft maneuverability requirements and the lift engines are sized to provide the additional lift necessary to achieve VTO.

(3) Aerodynamic stability is maintained within limits of 2% to 8% Mean Aerodynamic Chord (M.A.C.) from vertical takeoff to vertical landing, by positioning the wing and distributing the fuel load around the aircraft takeoff C.G.

(4) The lift/cruise air induction system is maintained aft of the cockpit to provide over-the-side pilot visibility.



(1) F_{N_V}/TOGW = 1.05 (Net)
(2) VTO Thrust Vectors Balanced about Takeoff C.G.
(3) Aerodynamic Stability within Limits (2% to 8% M.A.C.)
(4) Over-the-Side Pilot Visibility

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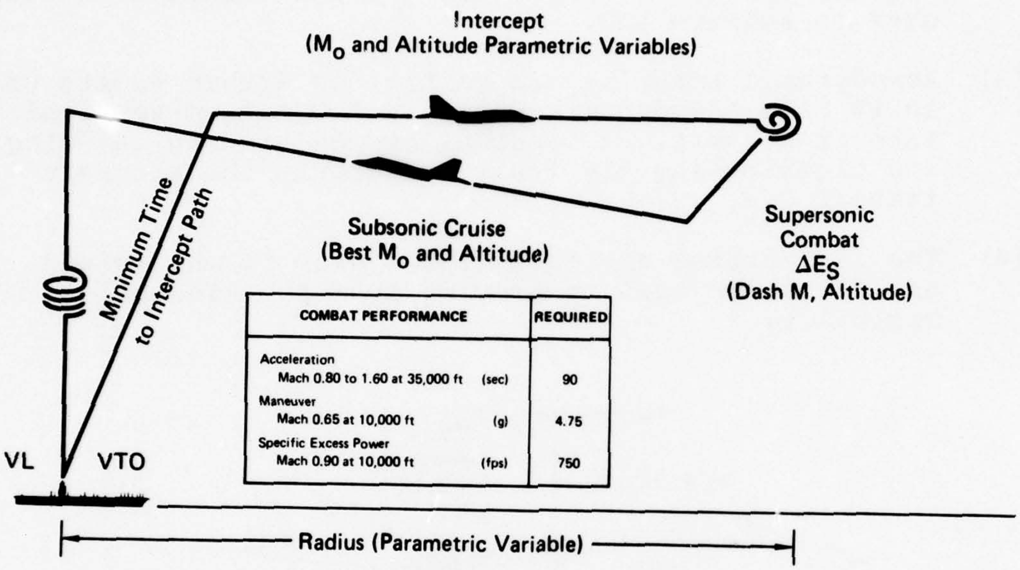
FIGURE 5
ENGINE/AIRFRAME INTEGRATION DESIGN CONSIDERATIONS

A V/STOL Deck Launched Intercept mission was used to establish aircraft internal fuel capacity requirements, Figure 6. Lift/Cruise engine size was established by the performance requirements also shown in Figure 6. The performance capabilities of each converged aircraft were computed for four predominantly subsonic missions, Figure 7, with two quantities of external fuel.



COMBAT PERFORMANCE		REQUIRED
Acceleration		
Mach 0.80 to 1.60 at 35,000 ft	(sec)	90
Maneuver		
Mach 0.65 at 10,000 ft	(g)	4.75
Specific Excess Power		
Mach 0.90 at 10,000 ft	(fps)	750

FIGURE 6
PARAMETRIC INTERCEPT DESIGN MISSION
Sizes Internal Fuel
Weapon Load = 2200 Lb (Retained)

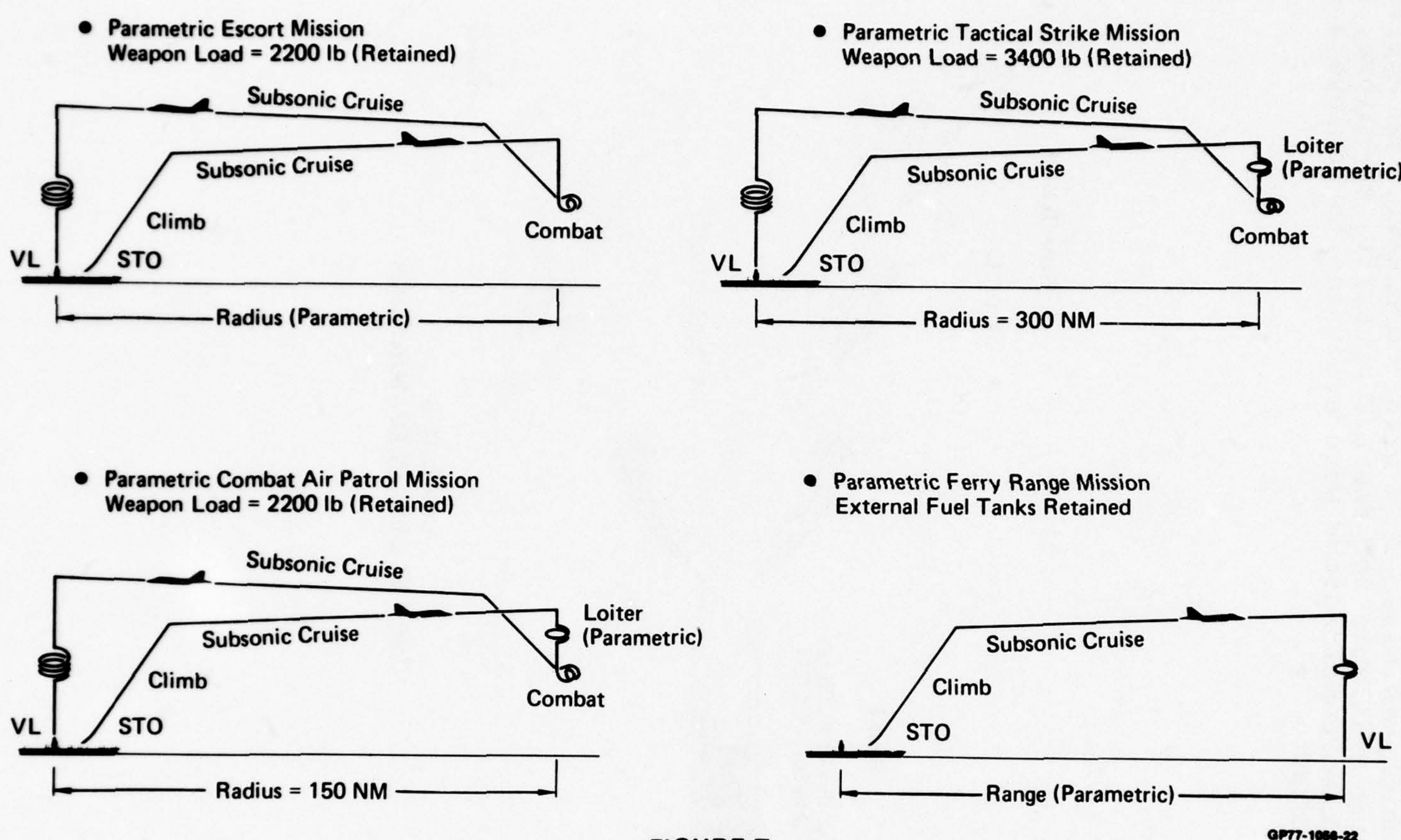


FIGURE 7
PARAMETRIC ALTERNATE MISSIONS (STOVL)

Fuel Load
- Internal
- Internal + (2) 300 Gallon Tanks
- Internal + (2) 600 Gallon Tanks

2.3 VCE-TF Engine/Airframe Evaluations - The VCE-TF can be used in either L + L/C or L/C aircraft configurations, Figure 8. The evaluations conducted in this program used representative V/STOL fighter requirements selected by MCAIR. The L + L/C aircraft evaluations were conducted using the airframe design variables which minimized TOGW with the FCE-TF. No applicable data base was available for the L/C aircraft, therefore, several engine/airframe combinations were evaluated to achieve a satisfactory design.

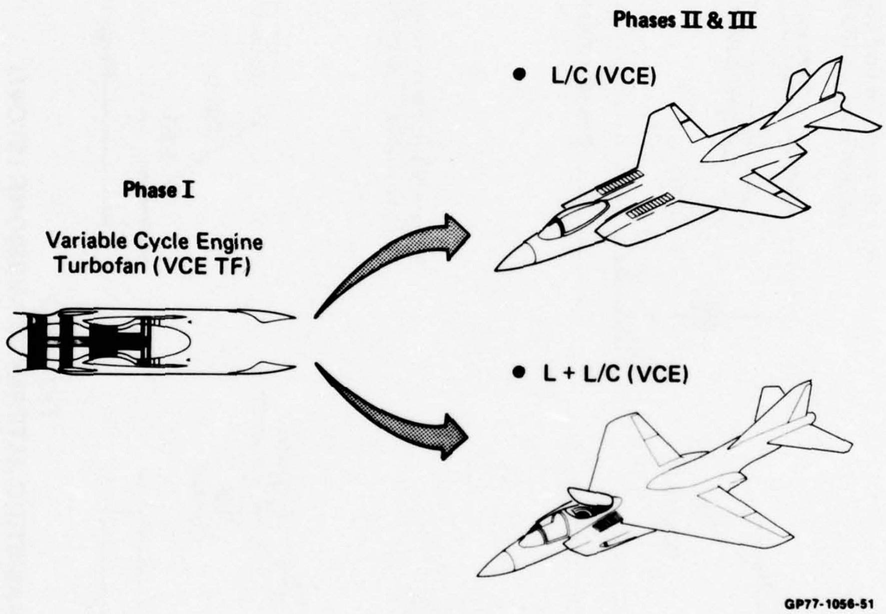


FIGURE 8
VCE-TF DESIGN EVALUATIONS

3. PARAMETRIC L + L/C AIRCRAFT EVALUATIONS

Correlations of parametric aircraft characteristics, developed using the V/STOL Fighter Design Evaluation Procedure, provide a valid basis for conducting aircraft/requirement interaction trade-offs and engine/airframe design selections. These correlations account for the complex interactions between engine and airframe design variables and aircraft size, performance, cost, and mission characteristics. The following sections briefly describe the data developed, examples of the aircraft/requirement interactions trade-offs which can be conducted, and the selection and comparison of engine/airframe designs meeting specific V/STOL fighter requirements.

3.1 Data Development - Eleven engine/airframe design and sizing variables were selected and used to develop correlations of advanced V/STOL aircraft characteristics. These correlations were developed using both advanced technology fixed cycle turbofan (FCE-TF) and variable geometry turbine turbojet (VGTTJ) engines.

3.1.1 FCE-TF Aircraft Data Development - The FCE-TF aircraft characteristic data correlations were developed using three airframe design, three engine design, and five sizing variables. These variables and their corresponding ranges of variation are shown in Figure 9.

Aircraft Design Variables

	Range of Variation
Airframe Design	
Combat Wing Loading	70-100 lb/ft^2
Wing Aspect Ratio	2.5-4.0
Wing Sweep	35^o-55^o
Engine Design	
Fan Pressure Ratio	3.2-4.0
Compressor Pressure Ratio	4.8-7.8
Engine Airflow Scheduling (ΔTAMB)	0^o-60^{o}F
Engine Sizing	
L/C VTO Thrust (% Maximum A/B)	55-80%
Combat Specific Energy (P_s)	100-300 ft/sec
Internal Fuel Sizing	
Intercept Radius	100-200 NM
Intercept Mach Number	1.4-2.0
Intercept Altitude	36,000-50,000 ft

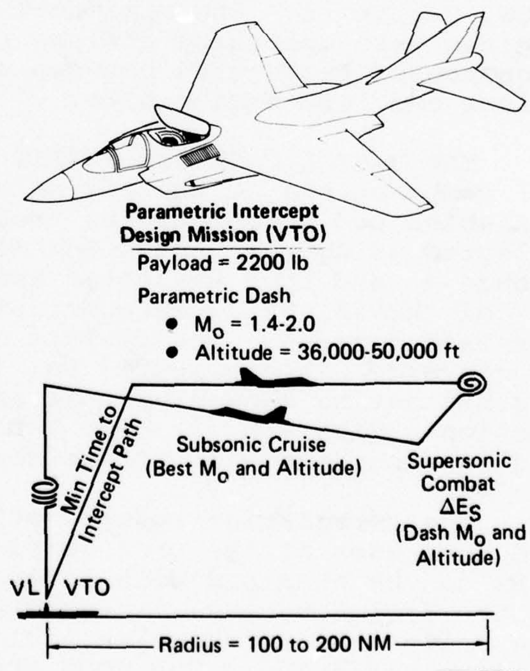


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FIGURE 9
DESIGN MATRIX
FCE-/TF Aircraft

A GE parametric V/STOL engine computer program, Reference 8, was used to obtain a consistently defined family of FCE-TF designs. Design (sea level static) fan pressure ratio (FPR) and compressor pressure ratio (CPR) were varied to obtain a wide range of overall pressure ratios and design bypass ratios (BPR). As FPR was increased from 3.2 to 4.0, BPR decreased from 1.2 to 0.6. An airflow scheduling variable, ΔTAMB, was varied from zero to sixty degrees to establish the off-design schedule of turbine inlet temperature, and thus engine airflow. As ΔTAMB was increased from 0° to 60°, turbine inlet temperature was increased to maintain maximum fan speed and therefore maximum corrected airflow. Typical variations of the engine characteristics with ΔTAMB are shown in Figure 10. This airflow scheduling variable provided the capability to conduct trades between engine performance at altitude and engine weight.

The lift/cruise engines were sized to provide the thrust required for the aircraft to meet a specified level of combat performance while the lift engines were sized by VTO thrust. Varying L/C engine size, by changing combat specific energy, provides the capability to conduct trades between combat performance requirements such as P_S, acceleration time and TOGW. Further, varying L/C engine VTO thrust provides the capability to conduct trades between L/C VTO nozzle exit temperature, lift engine size, and TOGW. In addition, the optimum thrust split between the lift engines and lift/cruise engines can be obtained. Design studies indicated that the level of L/C engine thrust during VTO had a significant impact on aircraft geometry and TOGW, Figure 11. The minimum TOGW was obtained when the L/C engines were operating at less than maximum power, as a consequence of trade-offs between aircraft length, internal fuel volume and lift engine size.

The V/STOL CADE and SURFIT procedures were used to evaluate 231 combinations of the engine/airframe design and sizing variables and correlate the results. The combinations were selected using the "Latin Square" procedure, discussed in Reference 4, and then evaluated using V/STOL CADE. Approximately 65% of the 231 variable combinations resulted in converged aircraft designs. The failure of 35% of the design combinations to converge was attributed to; (1) the higher bypass ratio engines having excessive fuel requirements to meet the Intercept mission radius and (2) high L/C engine VTO power settings resulting in excessive lift engine moment arm.

The correlation results were similar to those obtained in previous uses of the procedure. Typically, TOGW errors of up to $\pm$ 8% can be obtained with independent variables at the boundaries of the design matrix. These errors ranged from -3% to +4.5% for the engine and airframe variables and from -6% to +5% for the mission variables. The TOGW errors obtained with the engine and airframe variables in the regions of minimum TOGW were 2% or less. The V/STOL CADE output data obtained from each converged aircraft design consisted of aircraft size, weight, performance,

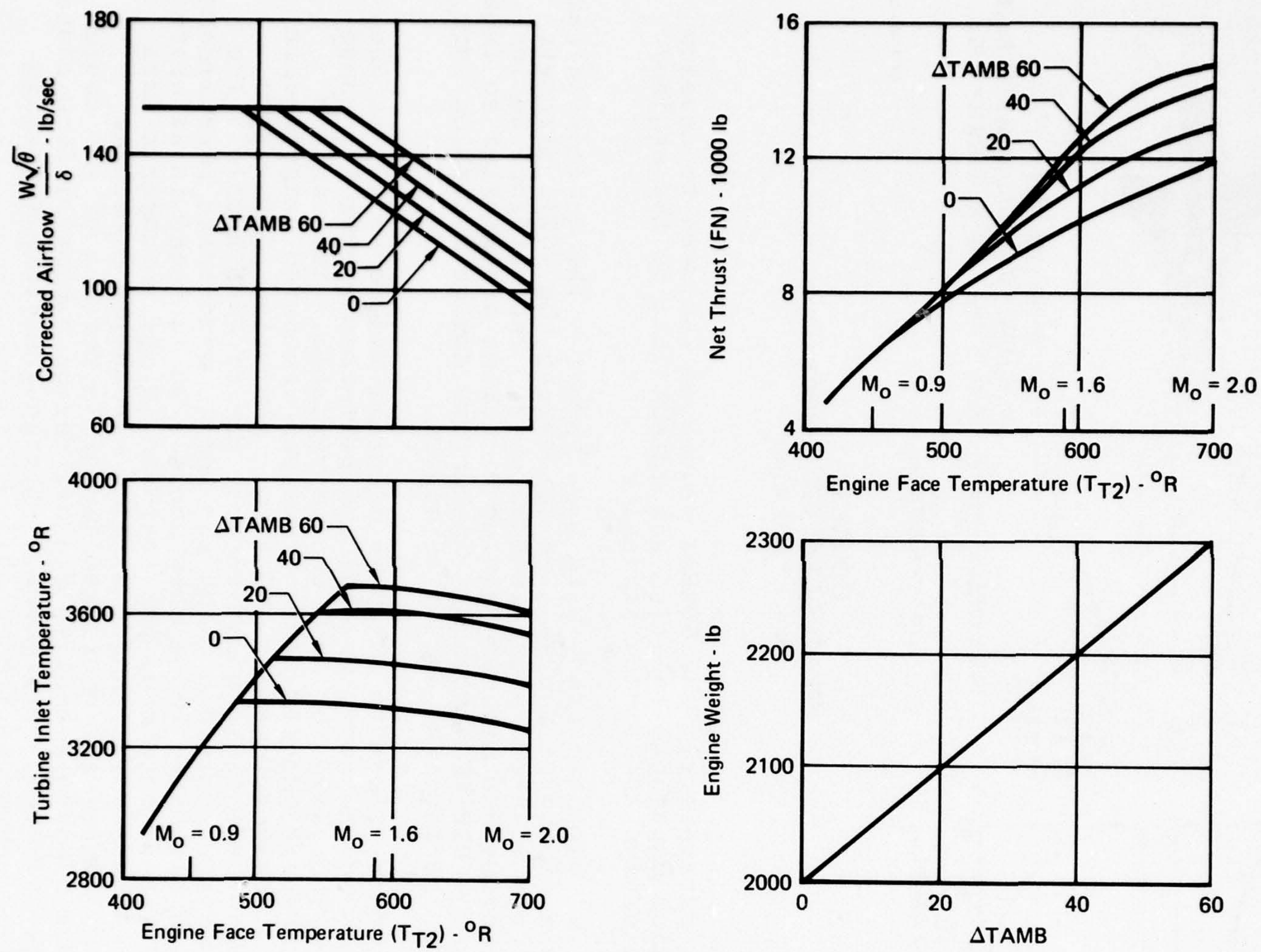

FIGURE 10
GE PARAMETRIC V/STOL ENGINE DECK
FCE-TF
Engine Airflow Scheduling
Altitude = 36,089 ft

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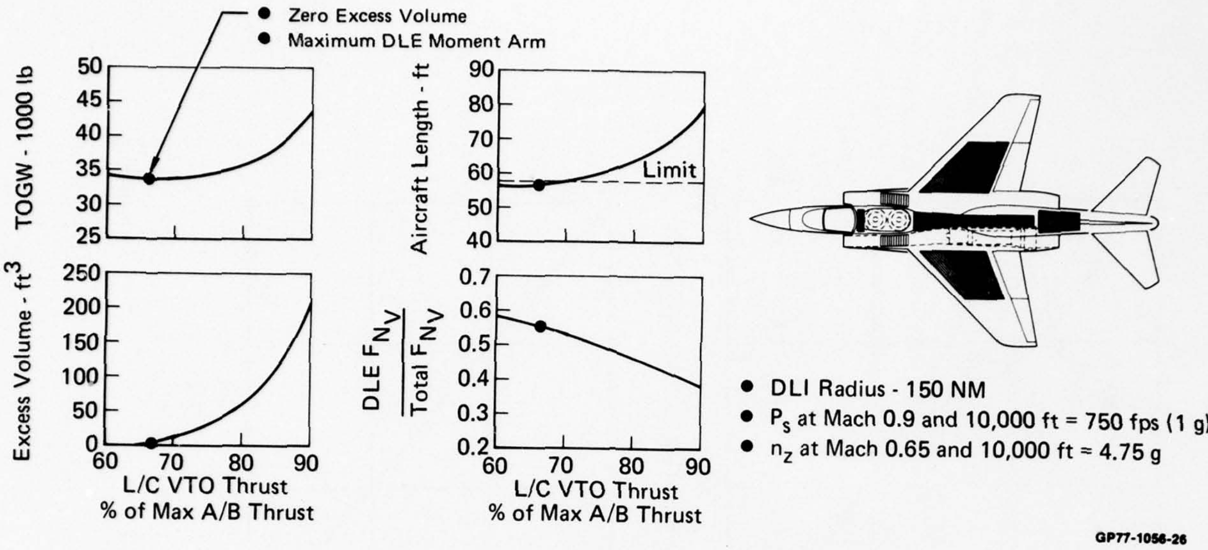


FIGURE 11
IMPACT OF L/C VTO THRUST
Input L + L/C Aircraft

and cost parameters. The SURFIT procedure was used to develop correlation equations relating the output data to the engine/airframe design and sizing variables.

3.1.2 VGTTJ Aircraft Data Development - The engine/airframe design and sizing variables used to develop the VGTTJ aircraft data correlations are shown in Figure 12. The airframe design and the engine and airframe sizing variables are similar to those used for the FCE-TF aircraft. The engine design variables were changed to reflect the use of turbojets.

A General Electric computer program, Reference 9, was used to compute engine size, weight, and performance over the range of values indicated for each engine variable. The engines defined by this program incorporate non-vectoring axisymmetric nozzles, therefore, weight and thrust vectoring performance adjustments were made to reflect the use of ADEN nozzle. The effects of ADEN nozzle cooling and nozzle unvectored performance (C_{f_g}) were estimated to be only about a 2% increase in aircraft TOGW and were, therefore, not included in the parametric data development. A VGTTJ engine airflow scheduling parameter, defined as compressor overspeed (% N_2) in percent of the design speed, was used to establish the off design engine airflow characteristics. Typical variations of the engine characteristics with %N_2 are shown in Figure 13.

Aircraft Design Variables

	Range of Variation
Airframe Design	
Combat Wing Loading	70-100 lb/ft^2
Wing Aspect Ratio	2.5-4.0
Wing Sweep	45^o-65^o
Engine Design	
Turbine Inlet Temperature (^{o}F)	2200-2600
Overall Pressure Ratio	10-20
Engine Airflow Scheduling (Percent N_2)	100-110
Engine Sizing	
L/C VTO Thrust (Percent Maximum A/B)	45-75%
Combat Specific Energy (P_s)	150-350 ft/sec
Internal Fuel Sizing	
Intercept Radius	100-200 NM
Intercept Mach Number	1.4-2.0
Intercept Altitude	36,000-50,000 ft

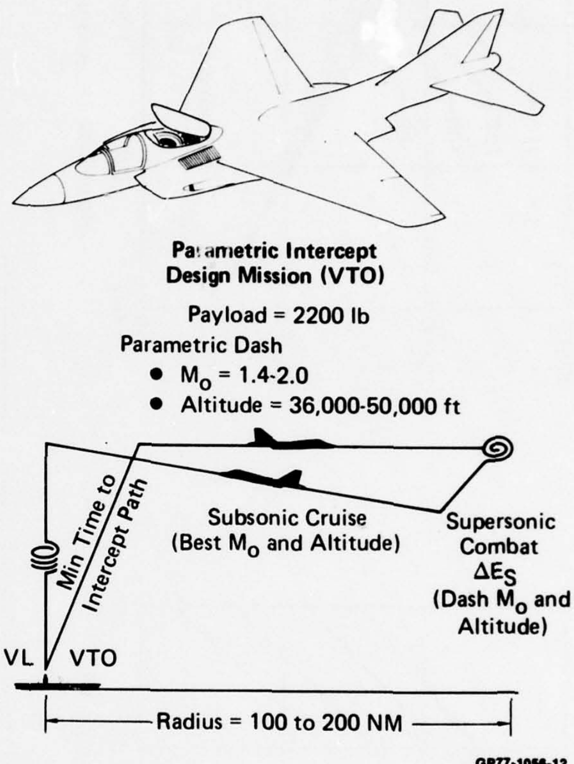


FIGURE 12
AIRCRAFT DESIGN MATRIX
VGTTJ Aircraft

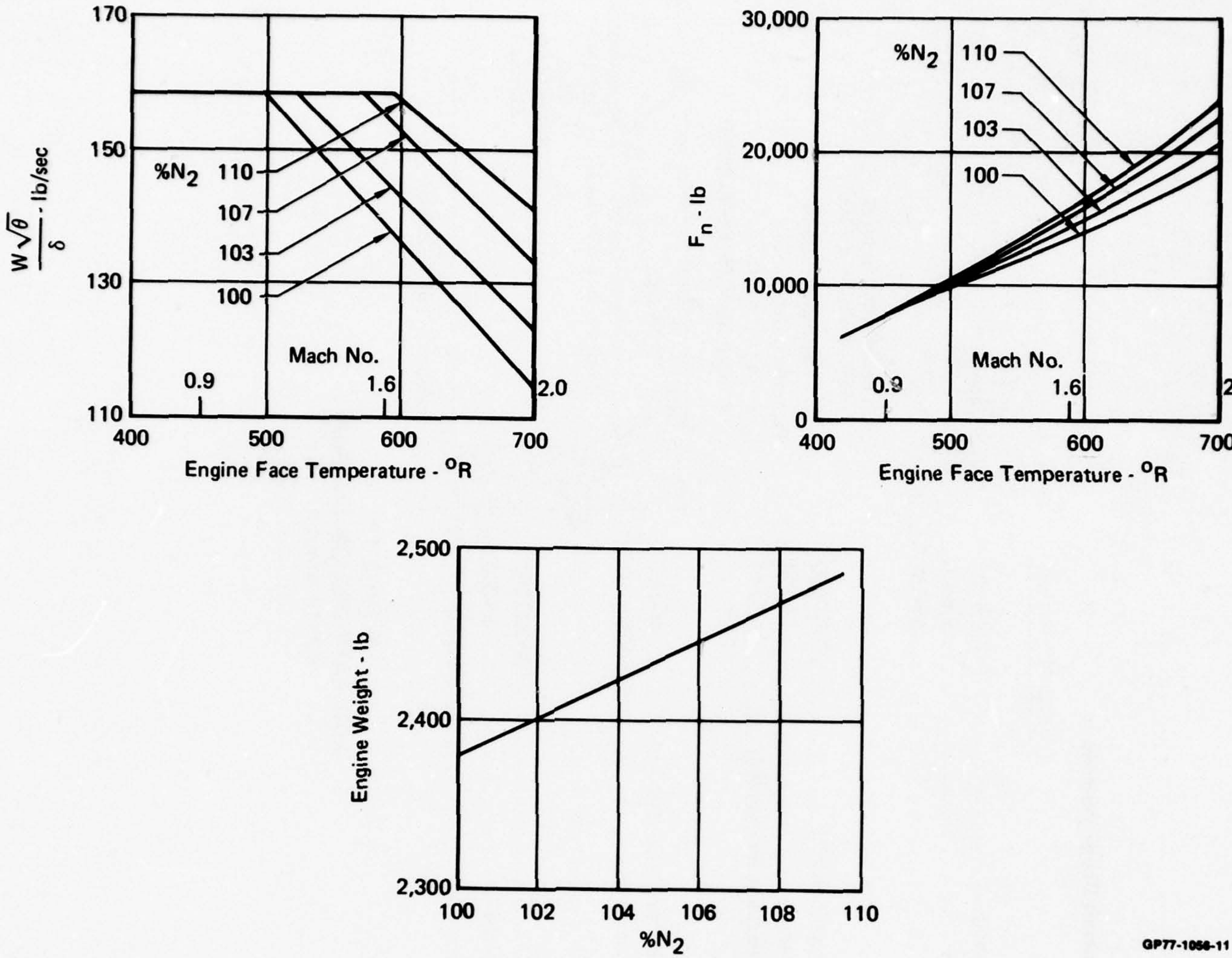


FIGURE 13
GE PARAMETRIC VGTTJ ENGINE DECK
Engine Airflow Scheduling
Altitude = 36,089 ft

Converged aircraft designs were obtained for approximately 96% of the 231 variable combinations evaluated. The SURFIT procedure was then used to develop correlation equations relating the characteristics of these aircraft to the engine/airframe design and sizing variables.

3.2 Engine/Airframe/Requirement Interactions - The aircraft characteristic data correlations obtained in this program afford the unique capability to conduct rapid and inexpensive investigations of aircraft/requirement interactions. The objective of such investigations is to identify the effects of design mission radius and performance requirements on engine and airframe design parameters, aircraft TOGW and cost, and alternate mission performance capabilities. Examples of this capability are presented below for both single mission and multi-mission design requirements.

3.2.1 Single Mission Engine/Airframe/Requirement Interactions - The Deck Launched Intercept (DLI) mission was used to illustrate the potential impact of design mission requirements on system characteristics. Interactions of the DLI mission radius and dash Mach number with aircraft TOGW were determined. These results are shown in Figures 14 and 15 for the FCE-TF and VGTTJ aircraft respectively. They can be used to estimate, for any desired combination of radius and dash Mach number, aircraft TOGW and the optimized design parameters. These data were generated by optimizing the aircraft design to produce minimum TOGW at all DLI radii and dash Mach numbers while meeting the specified thrust sizing performance requirements.

The engine and airframe design variables were not affected by changing intercept radius and dash Mach number; only the lift engine sizing variable, L/C VTO thrust, changed. Since the majority of the fuel was used in the supersonic dash segment of the mission, optimized engine variables produce minimum supersonic dash SFC as indicated by maximum FPR, minimum BPR, on the FCE-TF and maximum TIT on the VGTTJ. Low wing aspect ratio and high wing sweep were selected to minimize supersonic aircraft drag while wing loading was controlled by the N_Z = 4.75 g's requirement. Increasing radius and dash Mach number resulted in increased aircraft length to provide the necessary internal fuel volume. This increase in length, and hence available lift engine moment arm, made it possible to use higher L/C VTO power settings.

3.2.2 Multi-Mission Engine/Airframe/Requirement Interactions - Interactions between DLI and Fighter Escort mission radii and DLI TOGW are presented to illustrate potential multi-mission trade-offs. These results are shown in Figures 16 and 17 for the FCE-TF and VGTTJ aircraft respectively. The aircraft design was optimized to obtain minimum DLI TOGW while satisfying radii, P_S and N_Z requirements. Thus, these aircraft reflect the design compromises which produce minimum VTO TOGW while achieving the performance requirements of both the supersonic DLI and subsonic Fighter Escort missions.

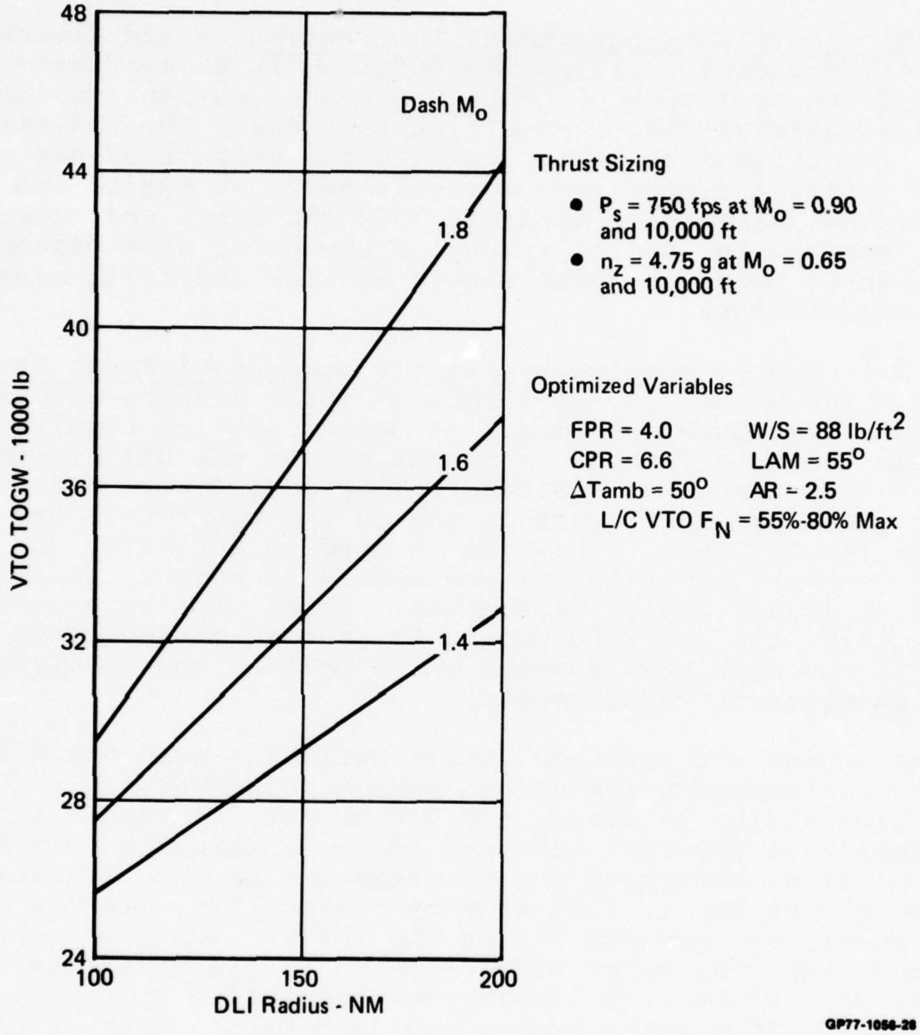
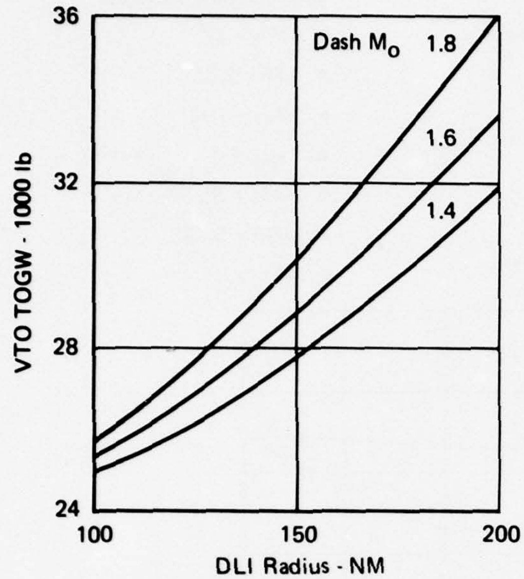


FIGURE 14
ENGINE/AIRFRAME/REQUIREMENT INTERACTIONS - DLI MISSION
Fixed Cycle Engine Turbofan (FCE-TF)



Thrust Sizing

- P_s = 750 fps at M_o = 0.90 and 10,000 ft
- n_z = 4.75 g at M_o = 0.65 and 10,000 ft

Optimized Variables

OPR = 17 W/S = 84 lb/ft^2
T.I.T = 2600°F LAM = 55°
% N_2 = 105 AR = 2.5
L/C VTO F_N = 45%-75% Max

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FIGURE 15
ENGINE/AIRFRAME/REQUIREMENT INTERACTIONS - DLI MISSION
Variable Geometry Turbine Turbojet (VGTTJ)

Sizing Requirements

- P_s at 0.9 M_o/10,000 ft/1 g ≥ 750 ft/sec
- Dash M_o = 1.6/Alt = 40,000 ft
- n_{z_s} at 0.65 M_o/10,000 ft ≥ 4.75 g
- P_s at Dash M_o & Alt ≥ 0 ft/sec
- Internal Fuel Only

Optimized Variables

- FPR = 3.5-4.0
- CPR = 6.6
- ΔTamb = 40-60 (Airflow Scheduling)
- W/S = 72-88
- LAM = 35-55
- AR = 2.5
- $(F_{N_V}/F_{N_{V_{max}}})$ = 0.45-0.80

TOGW

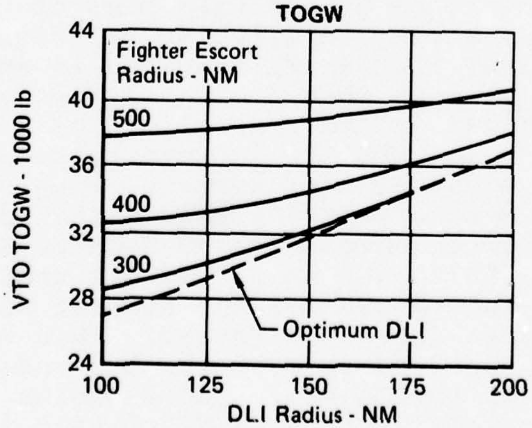

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FIGURE 16
ENGINE/AIRFRAME/REQUIREMENT INTERACTIONS - MULTI-MISSION
Fixed Cycle Engine Turbofan

Sizing Requirements

- P_s at 0.9 M_o/10,000 ft/1 g $\geq$ 750 ft/sec
- Dash M_o = 1.6/Alt = 40,000 ft
- n_{z_s} at 0.65 M_o/10,000 ft $\geq$ 4.75 g
- P_s at Dash M&H $\geq$ 0 ft/sec
- Internal Fuel Only

Optimization Variables

- OPR = 17
- TIT = 3,060
- $\%N_2$ = 105
- $F_{N_V}/F_{N_{V_{max}}}$ = 0.4-0.6
- LAM = 35-55
- WOS = 50-85
- AR = 2.5

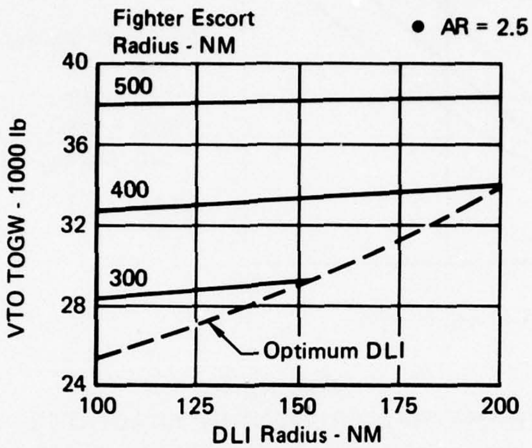

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FIGURE 17
ENGINE/AIRFRAME/REQUIREMENT INTERACTIONS - MULTI-MISSION
Variable Geometry Turbine Turbojet

The multi-mission requirements produced large variations in the engine and airframe design variables of the FCE-TF aircraft. For example, sizing to a 100 NM DLI radius and a 500 NM Fighter Escort radius, Figure 18, resulted in an optimum design fan pressure ratio of less than 3.6 while the design FPR selected for the DLI mission was at the upper limit of 4.0. Optimum design FPR decreased (increased BPR) to improve subsonic cruise SFC for the Fighter Escort mission. In addition, wing sweep (LAM) and wing loading (W/S) were decreased, Figure 18, to improve subsonic aerodynamic performance. As the Fighter Escort radius was decreased from 500 to 300 NM or the DLI radius requirement was increased from 100 to 200 NM, the Fighter Escort mission impact on the aircraft design decreased. This was a direct result of the fuel required to meet the DLI radius approaching that required to meet the Fighter Escort radius. Compressor pressure ratio and ΔTAMB variations had little impact on TOGW. Wing aspect ratio affected wing weight rather than DLI or Fighter Escort mission fuel usage.

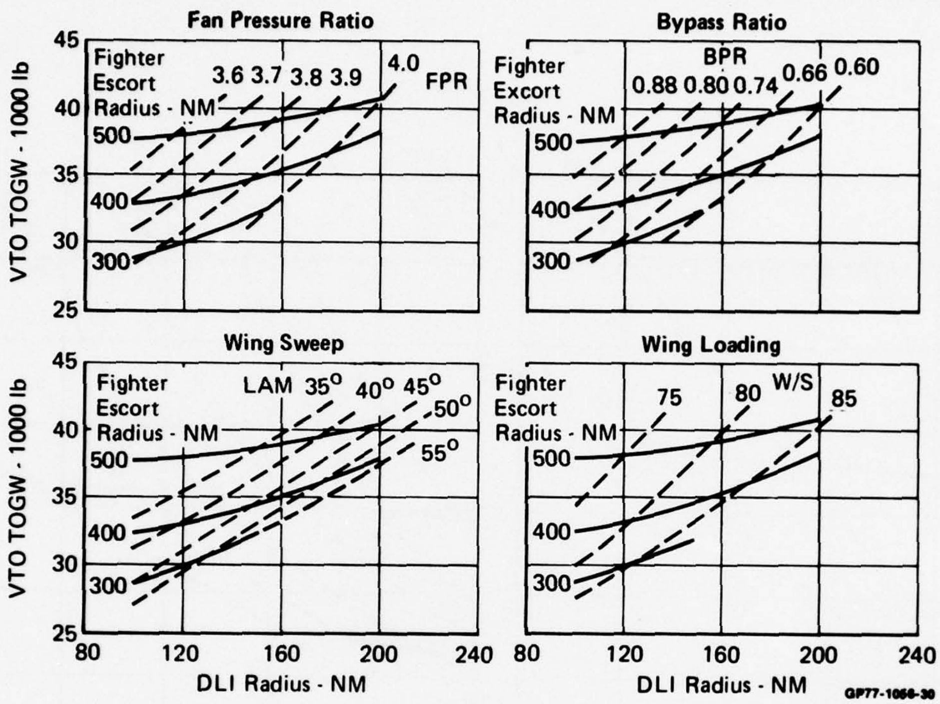

FIGURE 18
MULTI-MISSION INTERACTIONS
Fixed Cycle Engine Turbofan

The multi-mission requirements also produced large variations in the airframe design variables of the VGTTJ powered aircraft, but the engine variables were not affected. As indicated in Figure 19, wing sweep and wing loading were decreased to enhance subsonic cruise lift at low values of DLI radius. As DLI radius increased, the fuel required approached that required to meet the Fighter Escort radius and wing sweep and wing loading increased to reduce supersonic drag. The optimum engine design variables minimized supersonic dash SFC, taking advantage of the VGTTJ cycle flexibility to provide good subsonic cruise SFC for the Fighter Escort mission.

Sizing Requirements

- P_s at 0.9 M_o/10,000 ft/1 g ⩾ 750 ft/sec
- Dash M_o = 1.6/Alt = 40,000 ft
- n_{z_s} at 0.65 M_o/10,000 ft ⩾ 4.75 g
- P_s at Dash M&H ⩾ 0 ft/sec
- Internal Fuel Only

Optimization Variables

- OPR = 17
- T.I.T. = 3,060
- % N_2 = 105
- $F_{N_V}/F_{N_{V_{max}}}$ = 0.4 - 0.6
- LAM = 35-55
- W/S = 50-85
- AR = 2.5

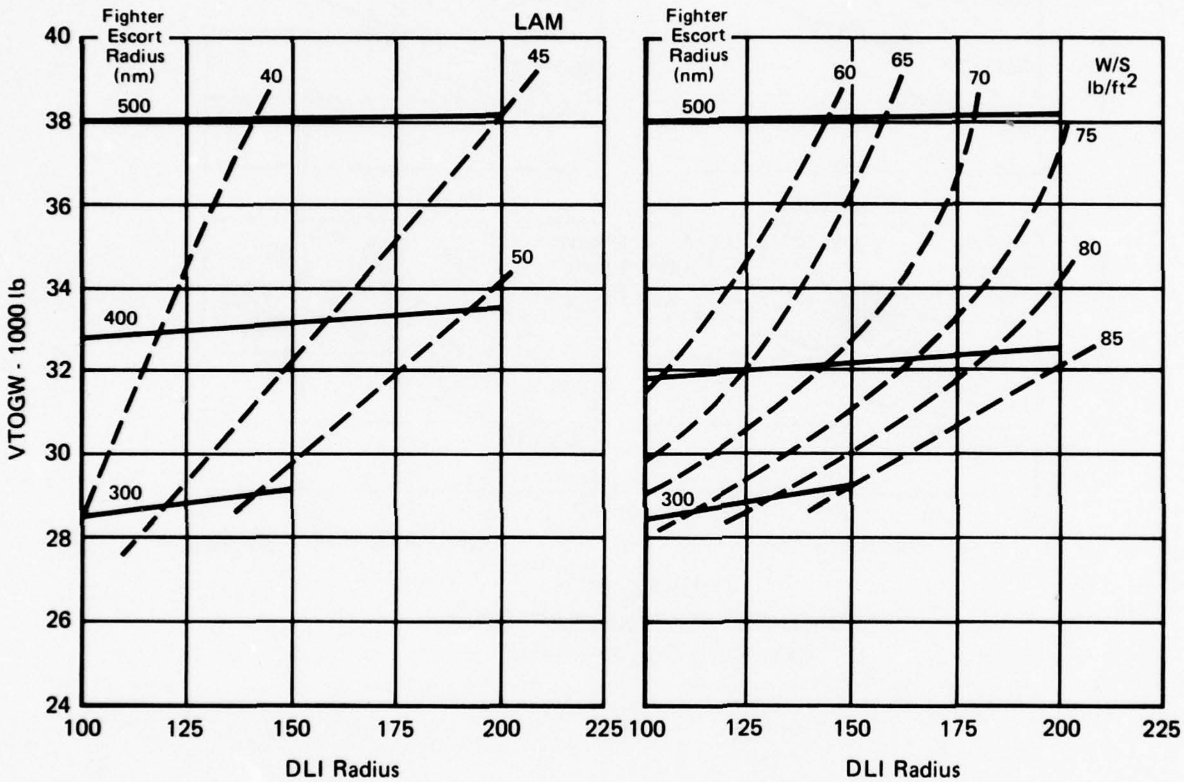

FIGURE 19
MULTI-MISSION INTERACTIONS
Variable Geometry Turbine Turbojet

3.3 <u>Design Selections and Comparisons</u> - Optimized aircraft designs were selected using both FCE-TF and VGTTJ engines to provide a consistent basis for comparison and assessment of variable cycle engine technology payoffs. The SEARCH optimization procedure was used to identify the minimum TOGW FCE-TF and VGTTJ aircraft capable of achieving the MCAIR selected V/STOL fighter requirements shown in Figure 20. These designs were then compared in terms of their TOGW, performance, and cost.

		Required
Mission Performance		
DLI Radius (Int Fuel)	(NM)	150/VTOL
Fighter Escort Radius (Ext Fuel)	(NM)	400/STOVL
Tactical Strike Loiter (Ext Fuel)	(hr)	2.0/STOVL
Combat Air Patrol Loiter (Ext Fuel)	(hr)	2.0/STOVL
Combat Performance		
Acceleration		
Mach 0.8 to 1.6 at 35,000 ft	(sec)	90
Maneuver		
Mach 0.65 at 10,000 ft	(g)	4.75
Specific Excess Power		
Mach 0.90 at 10,000 ft	(fps)	750

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FIGURE 20
MCAIR SELECTED V/STOL FIGHTER REQUIREMENTS

The selected FCE-TF and VGTTJ aircraft design are described in Figures 21 and 22, respectively. These figures show the range of independent design variables considered in the data base development, the values of the design variables selected to minimize TOGW, and the fuel sizing and thrust sizing variables which constrained the aircraft size. The FCE-TF and VGTTJ aircraft geometry and aerodynamic stability characteristics are included as Figures 23 and 24 respectively.

The aircraft are capable of meeting or exceeding alternate mission performance requirements using external fuel. The alternate mission performance capabilities of the aircraft are included in Figure 25. The Tactical Strike mission, with a two-hour loiter requirement at 20,000 feet was the most demanding. Approximately 1200 gallons of external fuel is needed to meet this requirement. The ADEN nozzle permits afterburning thrust to be used for STO, thereby allowing the takeoff distance requirement to be met with large fuel/weapon payloads. For example, Figure 26 shows that the FCE-TF aircraft, with a VTO TOGW of 32,650 lb can achieve the 400 ft short takeoff requirement at a TOGW in excess of 45,000 lb using intermediate power and a maximum TOGW in excess of 50,000 lb by using maximum afterburner. The 43,000 lb TOGW necessary to meet the Tactical Strike requirement results in a 200 feet STO with 10 knots wind-overdeck at intermediate power.

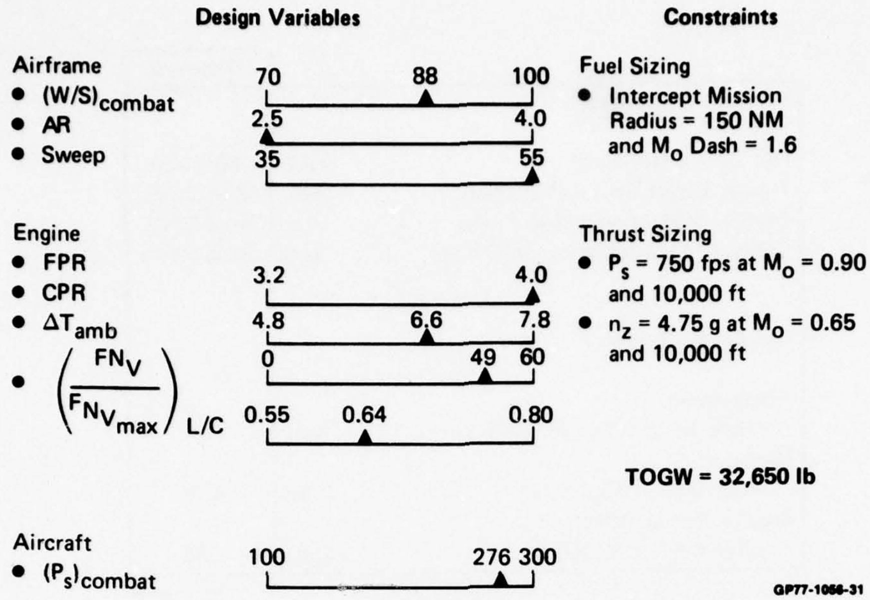


FIGURE 21
L + L/C AIRCRAFT DESIGN SELECTION
GE Fixed Cycle Turbofan L/C Engines

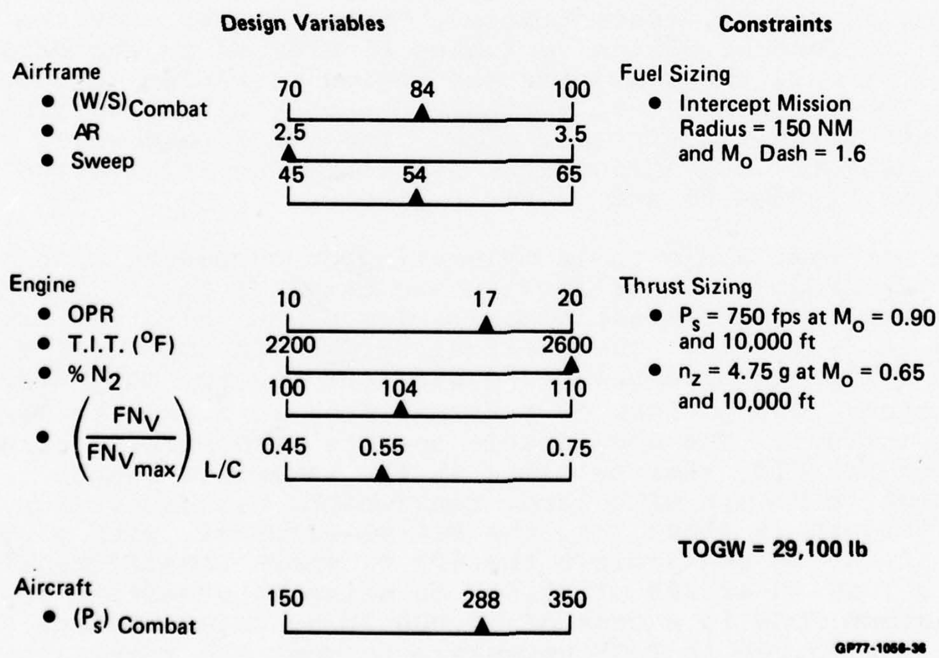
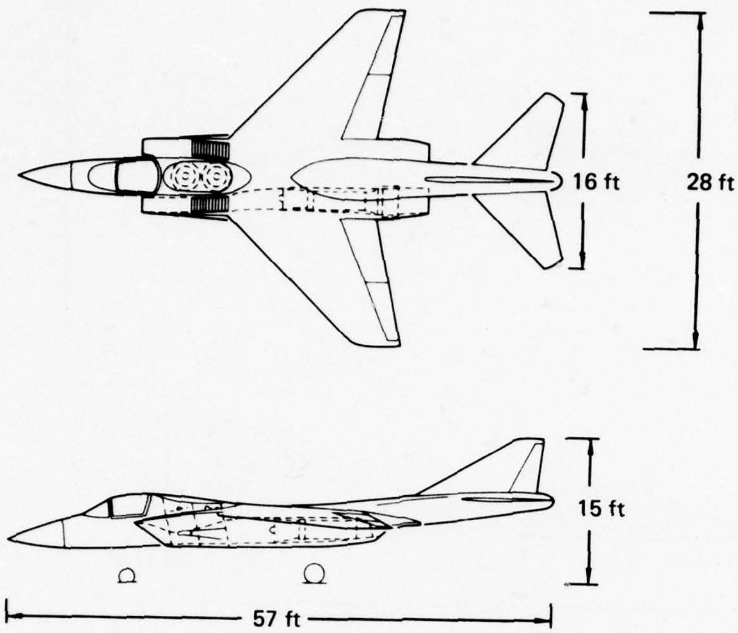


FIGURE 22
L + L/C AIRCRAFT DESIGN SELECTION
GE Variable Geometry Turbine Turbojet L/C Engines



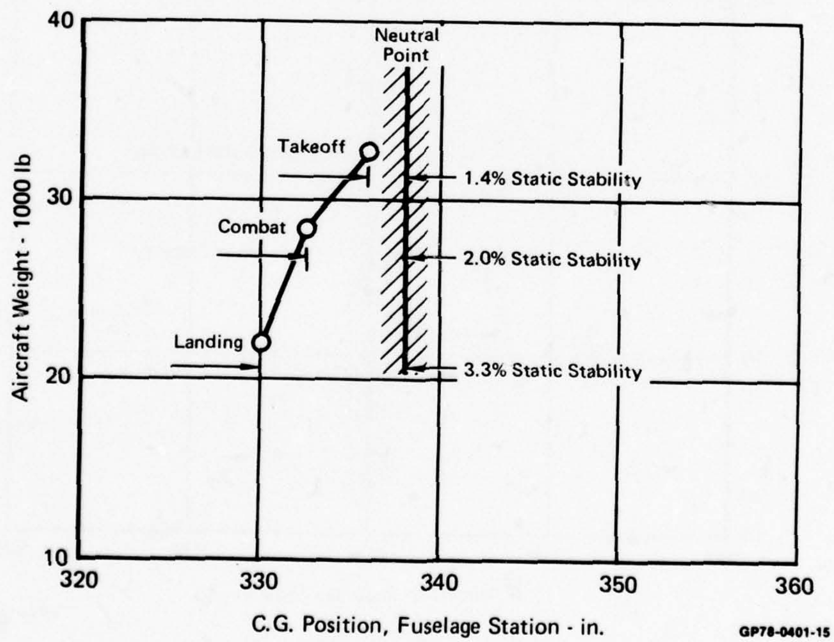


FIGURE 23
FCE-TF AIRCRAFT DESIGN CHARACTERISTICS

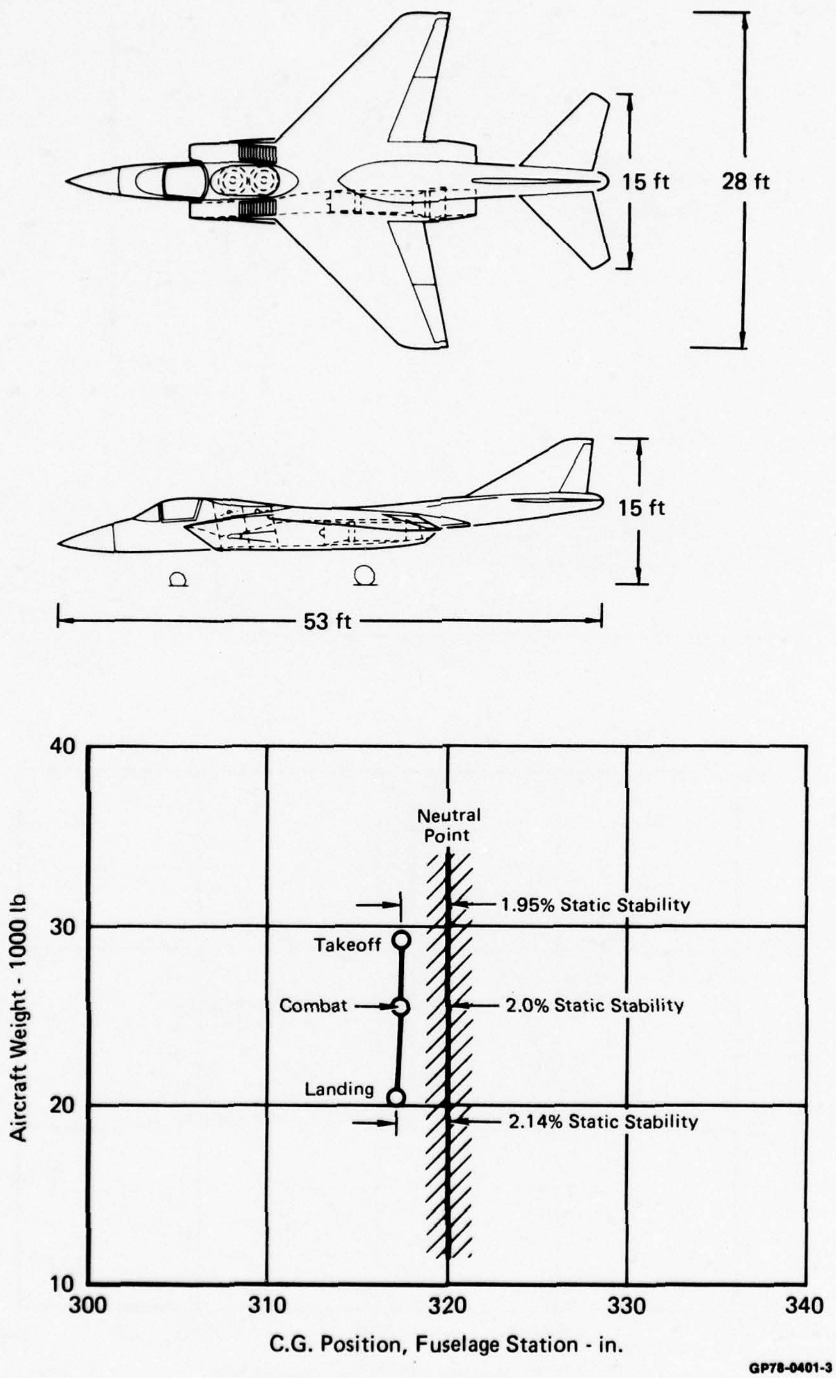
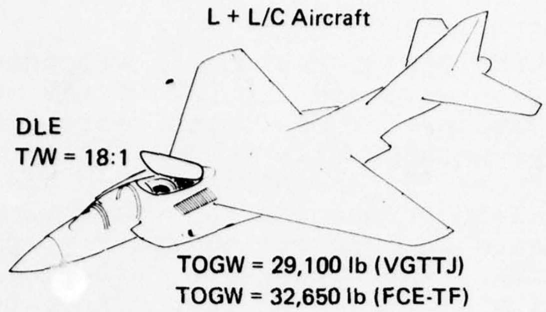


FIGURE 24
VGTTJ AIRCRAFT DESIGN CHARACTERISTICS



Performance		Required	Available (VGTTJ)	Available FCE-TF
P_s, Mach 0.90 at 10,000 ft	(fps)	750	750**	810
n_{z_s}, Mach 0.65 at 10,000 ft	(g)	4.75	4.75**	4.75**
DLI Rad (Int Fuel)	(NM)	150/VTOL	150**	150**
Fighter Escort Rad†	(NM)	400/STOVL	580	555
Tactical Strike Loiter*	(hr)	2.0/STOVL	1.95	2.0
Combat Air Patrol Loiter*	(hr)	2.0/STOVL	2.75	2.8

*(2) 600 gal. tanks **Sizing constraints †(2) 300 gal. tanks

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FIGURE 25
AIRCRAFT DESIGN SUMMARY

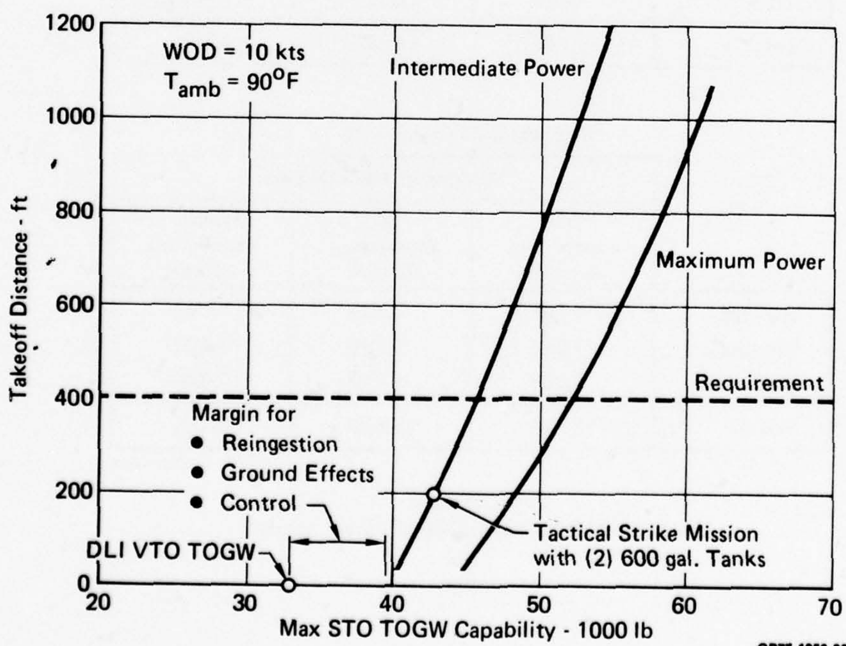

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FIGURE 26
STO CAPABILITY USING ADEN NOZZLE
Phase II Reference L + L/C Aircraft

The V/STOL Fighter Design Evaluation Procedure also provides the capability to estimate the LCC of the selected FCE-TF and VGTTJ aircraft designs. These costs represent the "cradle-to-grave" expenses associated with weapon system ownership. The results, shown in Figure 27, are divided into the three principle categories of RDT&E, Production, and Operations and Support (O&S). The RDT&E costs include all engineering development and flight test activities. The Production costs include all tooling, manufacturing, assembly and acceptance tests and component improvement programs. The O&S costs include the cost of personnel, facilities, spares, maintenance, training and fuel during the 15 year operational lifetime of the aircraft. The VGTTJ life cycle costs are approximately 9% less than those estimated for the FCE-TF aircraft.

Selected FCE-TF Aircraft

	Millions of 1976 Dollars		
	900 Production Aircraft	600 Production Aircraft	300 Production Aircraft
RDT&E	1,943	1,943	1,943
Production	9,078	6,671	4,044
O&S	8,445	5,721	2,943
Total	**19,466**	**14,335**	**8,930**

Selected VGTTJ Aircraft

	Millions of 1976 Dollars		
	900 Production Aircraft	600 Production Aircraft	300 Production Aircraft
RDT&E	1,844	1,844	1,844
Production	7,811	5,766	3,531
O&S	7,987	5,410	2,780
Total	**17,642**	**13,020**	**8,155**

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FIGURE 27
L + L/C AIRCRAFT LIFE CYCLE COST

4. VARIABLE CYCLE TURBOFAN AIRCRAFT EVALUATIONS

Engine/airframe design integration and performance analysis studies were required to establish a firm basis for evaluating the benefits derived from the use of the modulating bypass turbofan VCE concept, selected in Phase I. This GE variable cycle turbofan (VCE-TF), Figure 28, is a dual rotor, mixed-flow engine incorporating a variable stator compressor, high temperature rise combustor and a variable area low pressure turbine. In addition, the engine has a forward fan driven by the low pressure turbine rotor, an aft fan driven by the high pressure turbine rotor, and two bypass airflow ducts. The bypass ducts incorporate variable area bypass injectors (VABI's) to provide for mixing the inner and outer bypass flows and for mixing the bypass flow with the core flow. The mixed flow then exits through a single exhaust nozzle. The outer bypass duct is closed and the VCE-TF operates as a conventional mixed-flow turbofan during takeoff, transonic and supersonic flight conditions. At part power subsonic cruise and loiter flight conditions, the inner bypass flow is modulated by a combination of aft fan stator angle closure and opening of the outer bypass duct, thus, increasing the engine bypass ratio.

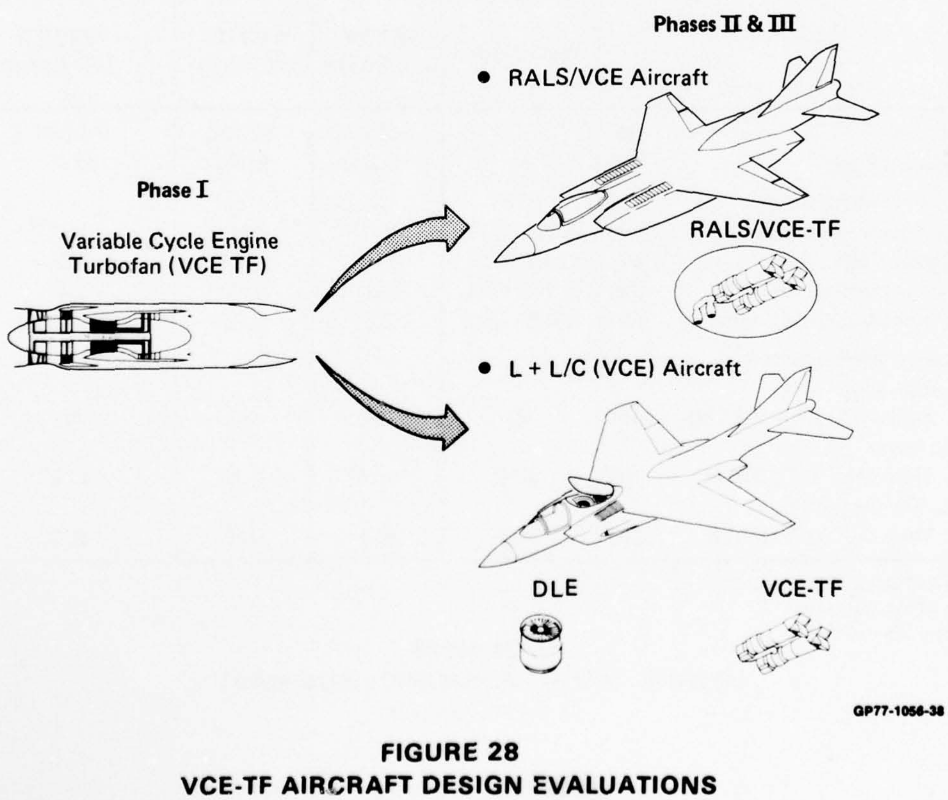

FIGURE 28
VCE-TF AIRCRAFT DESIGN EVALUATIONS

The VCE-TF can be used in conjunction with a lift engine or a derivative of the engine can be used to provide airflow to a remote augmentor lift system (RALS) during VTO, Figure 28. The RALS/VCE concept has the potential to eliminate the need for separate lift engines and thus, reduce V/STOL propulsion system life cycle costs. The VCE-TF integration and performance evaluations are discussed in Sections 4.1 and 4.2 for the L + L/C and L/C aircraft, respectively.

4.1 L + L/C Aircraft Evaluations - The VCE-TF payoff potential in a L + L/C aircraft was assessed using the airframe design and sizing constraints of the selected FCE-TF aircraft described in Section 3.3. The results, summarized in Figure 29, were obtained using a wing loading of 88 lb/ft^2, wing aspect ratio of 2.5, and a wing sweep of 55 degrees. The weight and performance characteristics of the FCE-TF and VGTTJ aircraft, also shown in Figure 29 for comparison, indicate competitive TOGW with increased alternate mission performance capability.

			L + L/C Aircraft Designs		
		Requirements	FCE-TF L/C Engine	VGT-TJ L/C Engine	VCE-TF L/C Engine
• TOGW	(lb)	–	32,650	29,100	29,600
• Internal Fuel	(lb)	–	10,600	9,100	8,960
• Mission Performance					
DLT Radius (Int Fuel)	(NM)	150/VTOL	150**	150**	150**
Fighter Escort Radius†	(NM)	400/STOVL	555	580	598
Tactical Strike Loiter*	(hr)	2.0/STOVL	2.0	1.95	2.2
Combat Air Patrol Loiter*	(hr)	2.0/STOVL	2.8	2.75	3.0
• Combat Performance					
Acceleration					
Mach 0.8 to 1.6 at 35,000 ft	(sec)	90	84	89	78
Maneuver					
Mach 0.65 at 10,000 ft	(g)	4.75	4.75**	4.75**	4.75**
Specific Excess Power					
Mach 0.90 at 10,000 ft	(fps)	750	824	750	832

†(2) 300 gallon tanks
*(2) 600 gallon tanks
**Sizing constraints

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FIGURE 29
WEIGHT AND PERFORMANCE SUMMARY
L + L/C Aircraft

4.2 L/C Aircraft Integration and Performance Evaluations - The payoff potential of a VCE-TF concept which produces all of the powered lift necessary for VTOL was evaluated in a L/C aircraft configuration. In this engine, the front portion of the split-fan is oversized to provide airflow to the remote augmentor lift system (RALS) for VTO.

Aircraft designs using the RALS/VCE concept, Figure 30, are highly sensitive to the relative levels of RALS and ADEN nozzle thrust during powered lift operation. This sensitivity reflects the requirement for balancec VTO thrust while maintaining an aircraft length compatible with carrier operations. Consequently, considerable configuration and engine design effort was required to obtain a viable RALS/VCE aircraft.

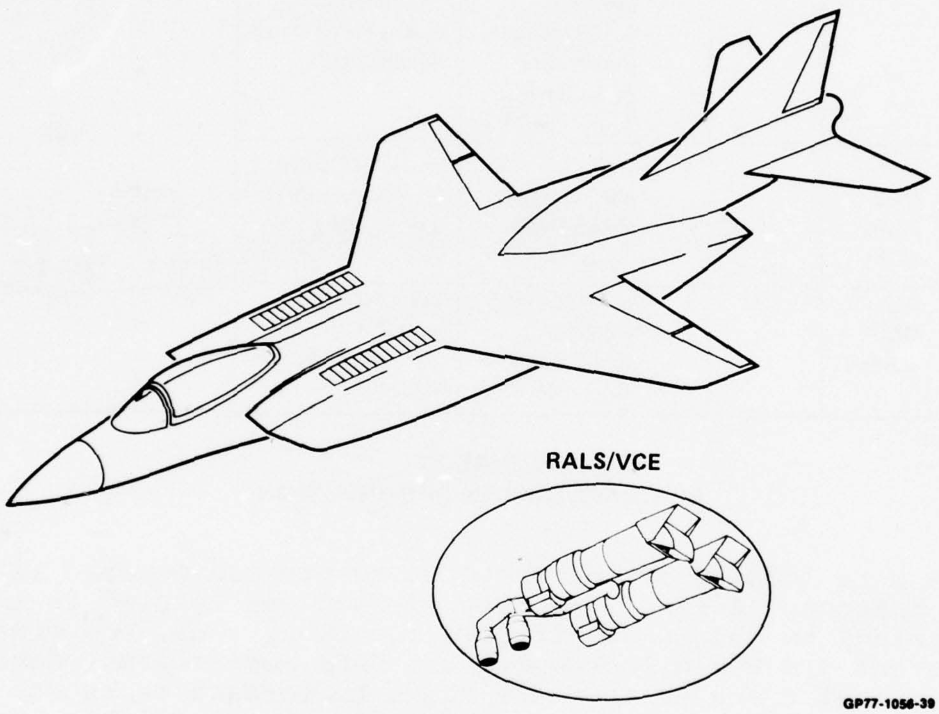
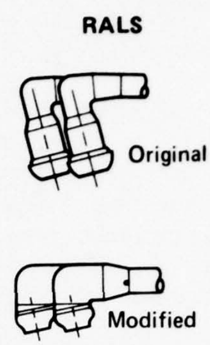


FIGURE 30
ADVANCED NAVY V/STOL FIGHTER
RALS/VCE Powered Lift System

In Phase II, a number of aircraft designs and propulsion system installations were investigated (Figure 31). The most attractive aircraft design obtained from that effort, the MCAIR Model 2008, was based on the D1 RALS/VCE (Figure 31). This engine which incorporated a modified RALS to minimize aircraft cross sectional area, had an ADEN/RALS thrust ratio equal to 1.8 for VTO. This thrust ratio required that the RALS be located forward of the aircraft C.G. 1.8 times further than the VCE ADEN

	RALS Configuration	$\frac{F_{N_{ADEN}}}{F_{N_{RALS}}}$	Aircraft Configurations	Results
Phase II	A1	3.0	• Twin RALS/VCE • Single RALS/VCE • Twin RALS/VCE – RALS Forward and Aft	VTO Thrust Balance Could not be Achieved
	C1	1.25	• Design Sketch Only	RALS Size Prohibitive
	D1	1.8	• Twin RALS/VCE – Modified RALS Design	Balance Questionable (Model 2008)
Phase III	D2	1.2	• Twin RALS/VCE – Modified RALS Design – Compressor Bleed for RCS – $T_{exit} = 2800^{o}F$	Balanced Configuration - Excess Performance (Model 2012)
	A3 (Dry Power VCE)	1.2	• Twin RALS/VCE – Modified RALS Design – $T_{exit} = 2000^{o}F$	Excessive Combat Fuel Consumption $\frac{Lb}{Fuel} = \frac{\Delta E_S \times W_F}{P_s}$
	A2 (Mini-Burner)	1.2	• Twin RALS/VCE – Modified RALS Design – $T_{exit} = 2000^{o}F$	Competitive with 2012 $\Delta TOGW = +400$ lb (Model 2014)



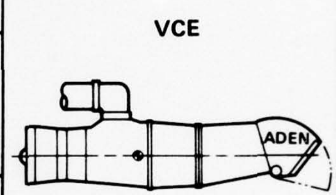


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FIGURE 31
AIRCRAFT DESIGN PROGRESSION

nozzles were located aft of the C.G. to provide powered lift thrust balance. A large quantity of fuel was located in the aft fuselage to obtain an aft C.G. location, thus, reducing the ADEN moment arm while increasing the RALS moment arm. Consequently, fuel transfer from aft tanks to forward tanks was required to control C.G. travel during wing-borne flight. The balance characteristics of this aircraft were therefore considered undesirable.

Phase III investigations encompassed VCE concepts specifically directed toward decreasing the ADEN/RALS thrust ratio in an effort to improve the aircraft balance characteristics. GE provided a RALS/VCE concept with an ADEN/RALS thrust ratio of 1.2, designated D2 in Figure 31, using interstage bleed air for the reaction control system, rather than fan bleed air as on the previous engines. This, then, provided additional fan discharge air for the RALS and thus, increased RALS thrust while decreasing ADEN thrust. With this thrust ratio for VTO, an aircraft configuration was designed which achieved all system require-

ments, Figure 32. The decreased ADEN/RALS thrust ratio provided the capability to operate with a more forward C.G. location. Thus, the fuel was distributed near the C.G. and satisfactory wing-borne flight stability was achieved with no fuel transfer, Figure 33.

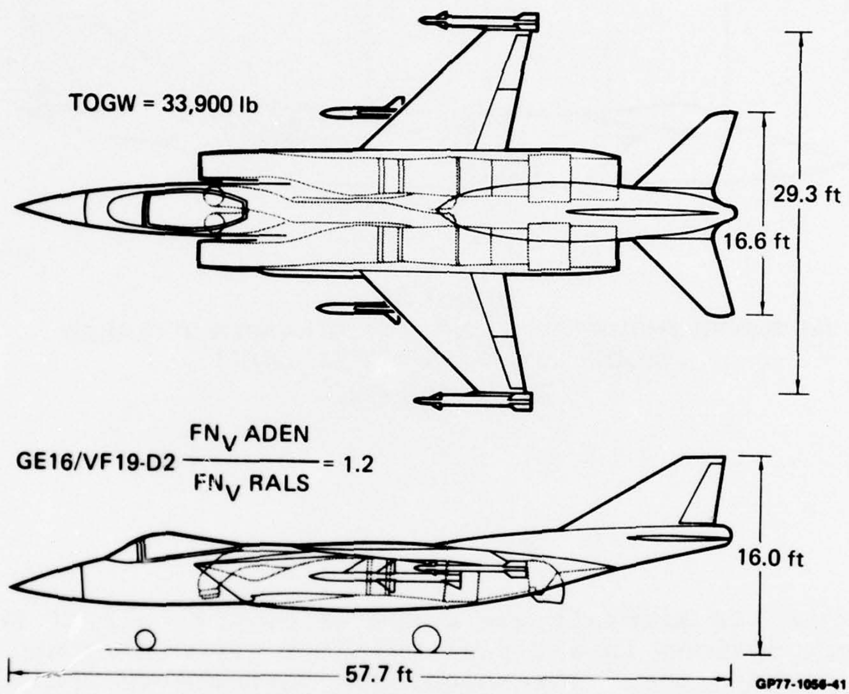

FIGURE 32
RALS/VCE-2012

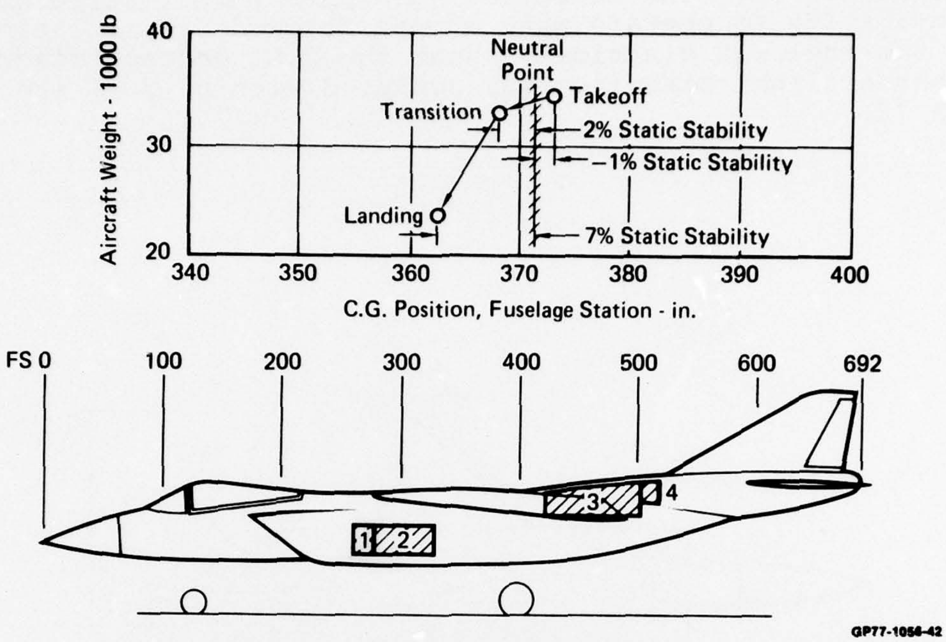

FIGURE 33
IMPROVED THRUST SPLIT - NO FUEL TRANSFER REQUIRED
MODEL 2012 RALS/VCE AIRCRAFT
TOGW = 33,900 lb

The RALS/VCE aircraft was competitive with all of the L + L/C aircraft designs in alternate mission capability and superior in combat performance. The weight and performance characteristics of these aircraft are compared in Figure 34. The engine cycle characteristics are compared in Figure 35. The RALS/VCE was sized by VTO thrust requirements and, as a result, exhibited excess thrust at combat conditions. Sizing the RALS/VCE for VTO substantially reduced acceleration time and increased P_s, but, also, increased TOGW. For the L + L/C designs, the L/C engine was sized by the combat performance requirements and the lift engines were subsequently sized to provide the additional lift required for VTO. However, if the L + L/C aircraft were sized to provide an equivalent combat Ps of 1270 feet/second, the resulting TOGW's would exceed 38,000 lb.

		L + L/C Aircraft Designs			RALS/VCE Aircraft (Model 2012)
	Requirements	FCE-TF L/C Engine	VGT-TJ L/C Engine	VCE-TF L/C Engines	
• TOGW (lb)	–	32,650	29,100	29,600	33,900
• Internal Fuel (lb)	–	10,600	9,100	8,960	10,100
• Mission Performance					
DLI Radius (Int Fuel) (NM)	150/VTOL	150**	150**	150**	150**
Fighter Escort Radius† (NM)	400/STOVL	555	580	598	570
Tactical Strike Loiter* (hr)	2.0/STOVL	2.0	1.95	2.2	2.0
Combat Air Patrol Loiter* (hr)	2.0/STOVL	2.8	2.75	3.0	2.7
• Combat Performance					
Acceleration					
Mach 0.8 to 1.6 at 35,000 ft (sec)	90	84	89	78	52
Maneuver					
Mach 0.65 at 10,000 ft (g)	4.75	4.75**	4.75**	4.75**	4.95
Specific Excess Power					
Mach 0.90 at 10,000 ft (fps)	750	824	750	832	1,270

†(2) 300 gallon tanks
*(2) 600 gallon tanks
**Sizing constraints

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FIGURE 34
AIRCRAFT WEIGHT AND PERFORMANCE SUMMARY

L/C Engine Designation	Engine Cycle Characteristics: FPR	BPR	OPR	Maximum TIT (°F)	VTO(3) Thrust/Weight
FCE-TF(1)	4.0	0.60	27	3180	6.7
VGTTJ(2)	–	0.00	13	2600	6.7
VCE-TF GE16/VVCE1-A1	4.0	0.50	24	3200	6.6
RALS/VCE GE16/VVCE5-D2	4.0	0.95	28	3200	6.4

Notes: (1) Obtained from GE parametric turbofan deck
(2) Obtained from GE parametric turbojet deck
(3) Based on 90° F day and 97% inlet recovery

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FIGURE 35
LIFT/CRUISE ENGINE CYCLE CHARACTERISTICS

Additional RALS/VCE evaluations were made, in an attempt to take advantage of the excess thrust available at combat flight conditions. These evaluations were conducted using a VCE designed without an afterburner and a VCE design which had limited augmentation capability. For both of these designs, the VTO exhaust gas temperatures were limited to a maximum of 2000°F as opposed to 2800°F for the fully augmented systems. The dry power VCE was not competitive due to its excessive combat fuel consumption. However, an aircraft design competitive with the Model 2012 aircraft was obtained using the VCE design having limited augmentation capability (Figure 31). Detailed discussions of these evaluations are included in Reference 3.

Direct lift engine technology, expressed in terms of thrust-to-weight ratio, can have a significant impact on aircraft TOGW. As indicated previously, the L + L/C analyses in this program were conducted using DLE's with an 18:1 thrust/weight ratio. The effect of reducing DLE thrust/weight ratio from 18:1 to 15:1 was determined by resizing the L + L/C aircraft designs to meet the Intercept mission and performance requirements. These results are shown in Figure 36. The RALS/VCE aircraft is also included for comparison, since reducing lift engine T/W ratio makes the RALS/VCE even more competitive. Decreasing the T/W ratio of the DLE to 15:1 resulted in approximately a 3% increase in design mission TOGW and slight decreases in alternate mission capability. Combat performance was not affected.

			Requirement	L + L/C Aircraft Designs						RALS/VCE Aircraft (Model 2012)
				DLE T/W = 18			DLE T/W = 15			
				FCE-TF	VGTTJ	VCE-TF	FCE-TF	VGTTJ	VCE-TF	
• TOGW		(lb)	–	32,650	29,100	29,600	33,515	29,915	30,400	33,900
• Internal Fuel		(lb)	–	10,600	9,100	8,960	10,835	9,300	9,180	10,100
• Mission Performance										
	DLI Rad (Int Fuel)	(nm)	150/VTOL	150**	150**	150**	150**	150**	150**	150**
	Fighter Escort Rad†	(nm)	400/STOVL	555	580	598	548	574	590	570
	Tactical Strike Loiter*	(hr)	2.0/STOVL	2.0	1.95	2.2	2.0	1.9	2.20	2.0
	Combat Air Patrol Loiter*	(hr)	2.0/STOVL	2.8	2.75	3.0	2.8	2.7	2.95	2.7
• Combat Performance										
Acceleration										
	Mach 0.8 to 1.6 @ 35,000 ft	(sec)	90	84	89	78	84	88	78	52
Maneuver										
	Mach 0.65 @ 10,000 ft	(g)	4.75	4.75**	4.75**	4.75	4.75	4.75**	4.75**	4.95
Specific Excess Power										
	Mach 0.90 @ 10,000 ft	(fps)	750	824	750**	832	825	750	832	1,270

†(2) 300 gallon tanks
*(2) 600 gallon tanks
**Sizing constraints

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FIGURE 36
EFFECT OF LIFT ENGINE THRUST/WEIGHT ON AIRCRAFT TOGW

5. VCE PAYOFF ASSESSMENTS

The VCE payoffs were assessed in terms of TOGW, life cycle cost, performance and operational flexibility which provide a measure of the cost effectiveness of the weapon system. General Electric indicated the VCE-TF engine costs would be higher than those for a FCE-TF and VGTTJ engine of comparable size. For example, the RDT&E and production costs of a VCE-TF would be 18% and 11% higher respectively than a FCE-TF engine sized to the same sea level static thrust. Therefore, for the VCE-TF to be cost effective, these higher engine related costs must be offset by reduced airframe related cost, or, the VCE-TF must provide increased performance and/or operational flexibility. The VCE payoff assessments were conducted using the results obtained from the fixed cycle turbofan, variable geometry turbine turbojet and variable cycle turbofan engine/airframe evaluations.

Assessments were made to determine the impact, on aircraft life cycle cost, of variable engine component related TOGW reductions or elimination of separate lift engines. These assessments were made relative to the L + L/C aircraft powered by advanced technology fixed cycle turbofan (FCE-TF) lift/cruise engines and advanced technology lift engines. The TOGW of this FCE-TF aircraft was 32,650 lb when sized to a 150 NM DLI mission radius and representative combat performance requirements, and its LCC was estimated to be in excess of 19 billion dollars. The lowest TOGW and aircraft LCC were obtained for the L + L/C aircraft powered by simple single-spool variable geometry turbine turbojet (VGTTJ) lift/cruise engines, Figure 37. A substantial TOGW reduction was also obtained for the L + L/C aircraft powered by more complex variable cycle turbofan (VCE-TF) lift/cruise engines. The LCC cost for the VCE-TF aircraft, Figure 37, were competitive with the FCE-TF. Elimination of the cost of developing and producing separate lift engines, 1.67 billion dollars (Figure 38), made the RALS/VCE aircraft competitive in LCC with the reference FCE-TF aircraft. However, eliminations of the lift engines was not enough to reduce LCC to the levels obtained with the turbojet.

The airframe and engine cost for the three L + L/C aircraft and the RALS/VCE aircraft were also compared. The results of this comparison are shown in Figure 38. The cost payoffs achieved with the VGTTJ engine reflect lower TOGW and therefore lower air frame cost and lower engine production cost resulting from the reduced engine size. The lower TOGW and therefore lower airframe cost for the VCE-TF aircraft, relative to the FCE-TF aircraft, offset increased engine development cost and resulted in production cost competitive with the FCE-TF. The cost payoffs achieved with the RALS/VCE, relative to the FCE-TF, were primarily due to reduced engine production costs.

Assessments of the combat performance capability of the aircraft designs were made. Each V/STOL fighter achieved at least the required levels of combat performance. However, the RALS/VCE

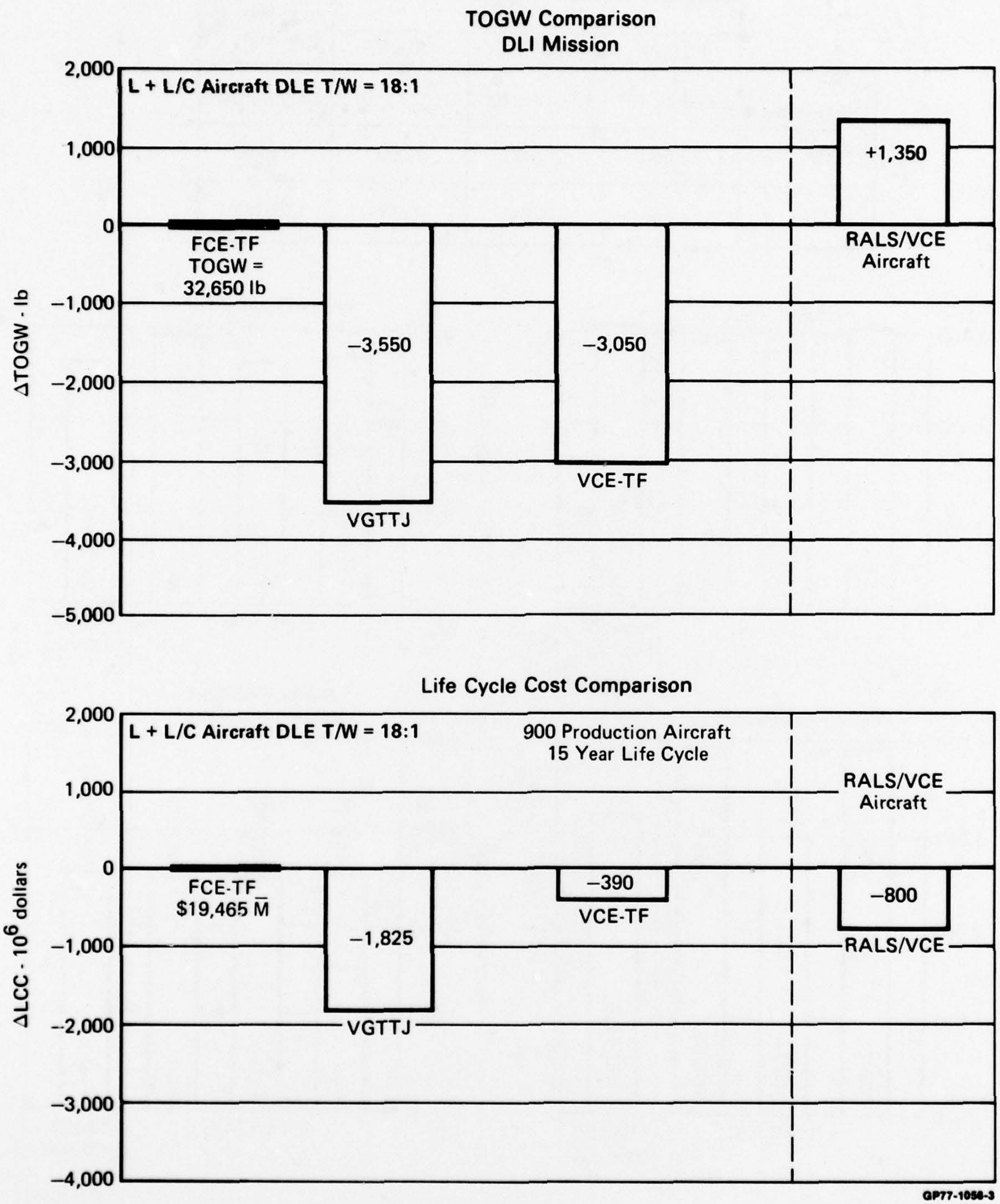

FIGURE 37
VCE PAYOFF ASSESSMENT - TOGW AND LCC

	L + L/C Aircraft			RALS/VCE Aircraft
	FCE-TF	VGTTJ	VCE-TF	
LCC (1976 Dollars)	19.466×10^9	17.642×10^9	19.077×10^9	18.668×10^9
TOGW (lb)	32,650	29,100	29,600	33,900
$F_{n_{SLS}}$ L/C (lbf)	16,465	13,880	14,783	23,975

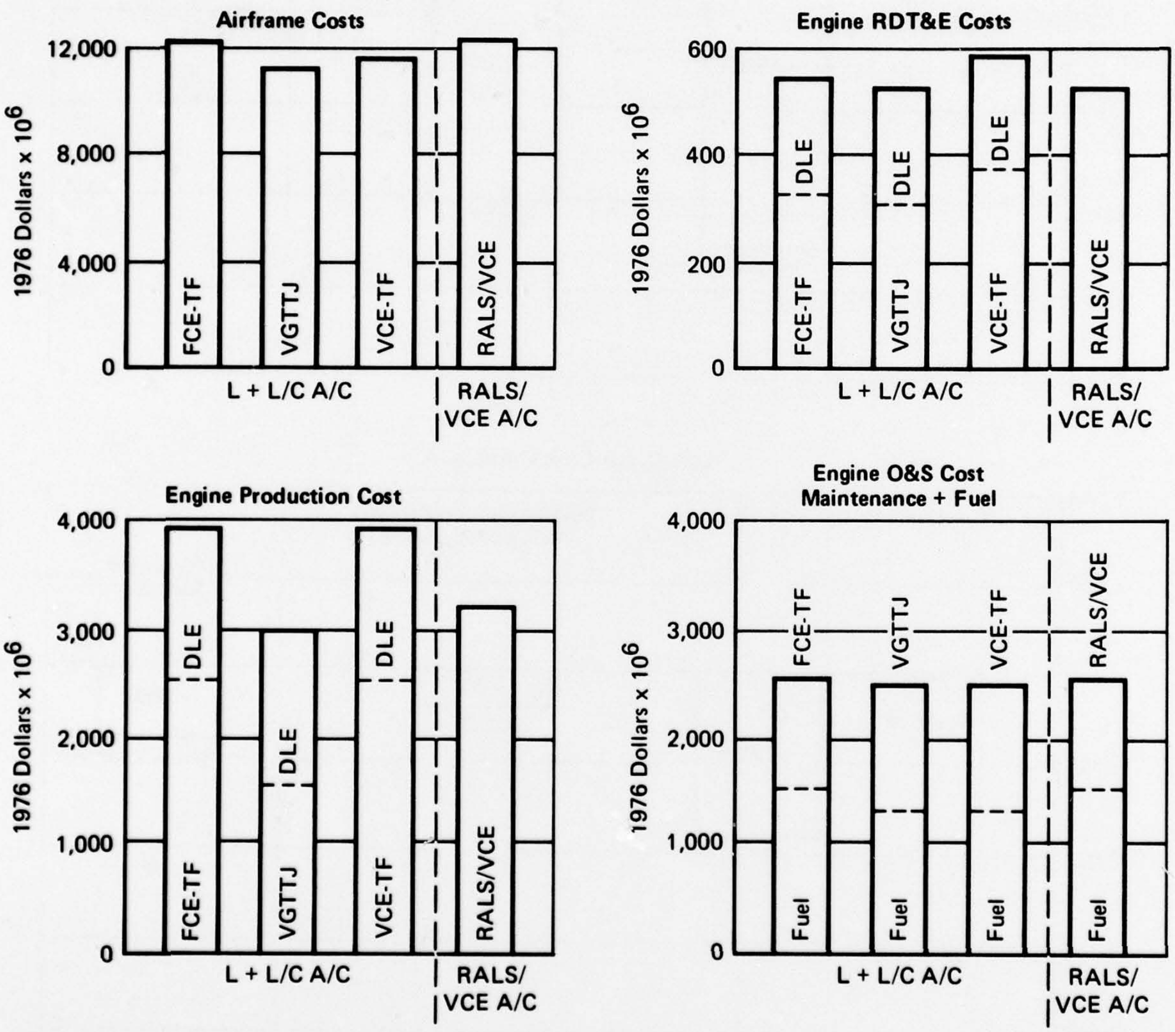

FIGURE 38
COST COMPARISONS - 900 AIRCRAFT

engines were sized by VTO requirements and, as the result, exceeded the required combat performance level as indicated in Figure 39. Although the RALS/VCE was 4% heavier than the reference aircraft, this aircraft had 40% - 50% more combat Ps and acceleration capability than used as representative for advanced systems for this example. If higher combat performance levels than those used in this study are required, the RALS/VCE aircraft will become more competitive. For example, the VGTTJ aircraft was scaled to provide a combat Ps level, 1270 ft/sec, equivalent to that of the RALS/VCE aircraft. The estimated LCC for the scaled turbojet aircraft exceeded the RALS/VCE life cycle cost by 10% or approximately two billion dollars, Figure 40.

The operational flexibility achieved through the use of variable cycle engine features was assessed by determining the fuel required to achieve the 400 NM Fighter Escort mission radius. The results are shown in Figure 41. A 13% to 15% fuel savings was obtained relative to the FCE-TF for both L + L/C configurations. Only a 3% fuel savings was obtained with the RALS/VCE aircraft design for which the L/C engine was size by the VTO requirement and therefore, was oversized for optimal fuel utilization.

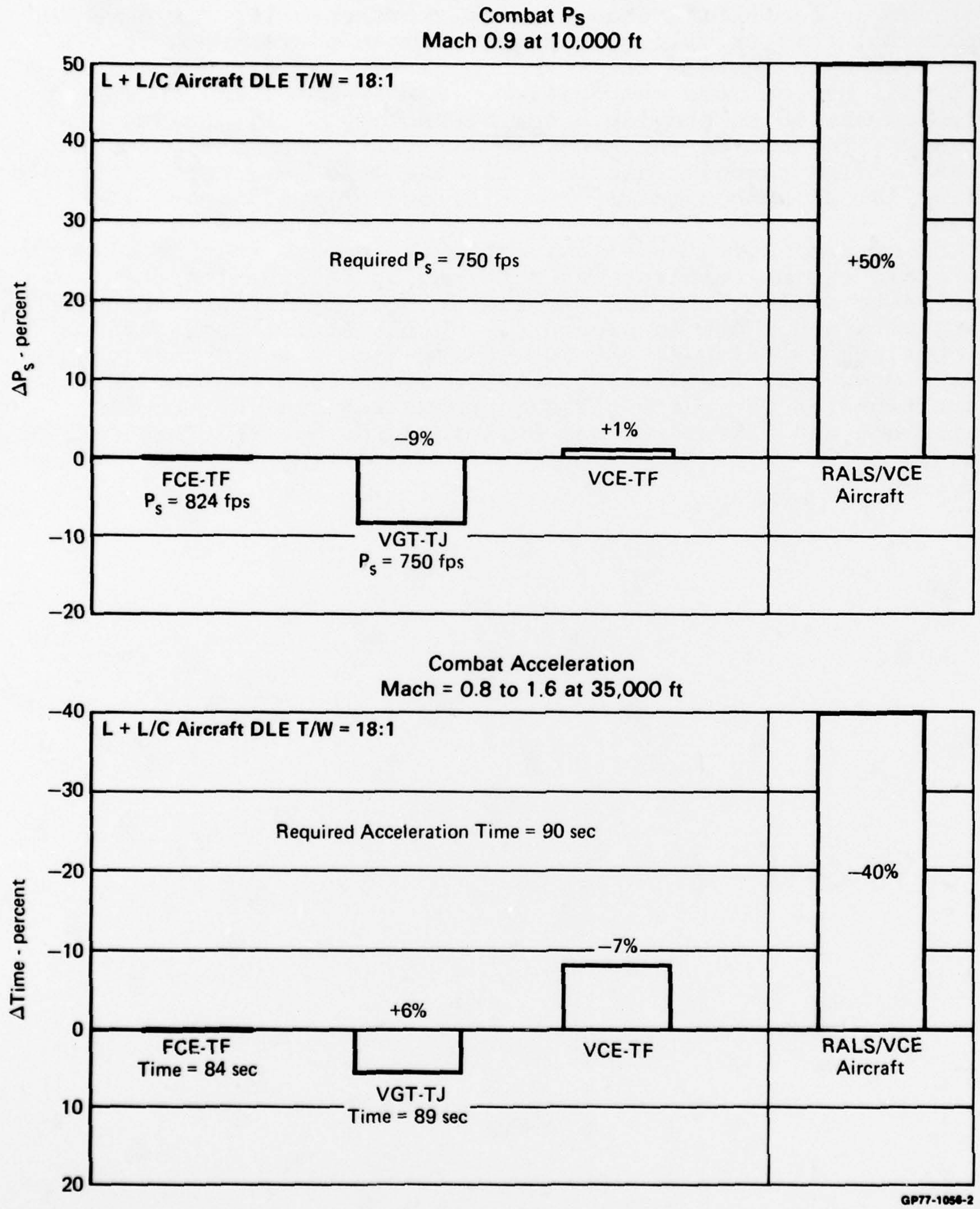

FIGURE 39
VCE PAYOFF ASSESSMENT - COMBAT PERFORMANCE

Combat P_s = 1270 ft/sec at Mach 0.9 @ 10,000 ft

	Millions of 1976 Dollars	
	L + L/C (VGTTJ) Aircraft	RALS/VCE Aircraft
RDT&E	2,137	1,921
Production	9,259	8,402
O&S	9,212	8,345
Total	**20,608**	**18,668**

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FIGURE 40
LIFE CYCLE COST FOR EQUIVALENT PERFORMANCE
900 Production Aircraft

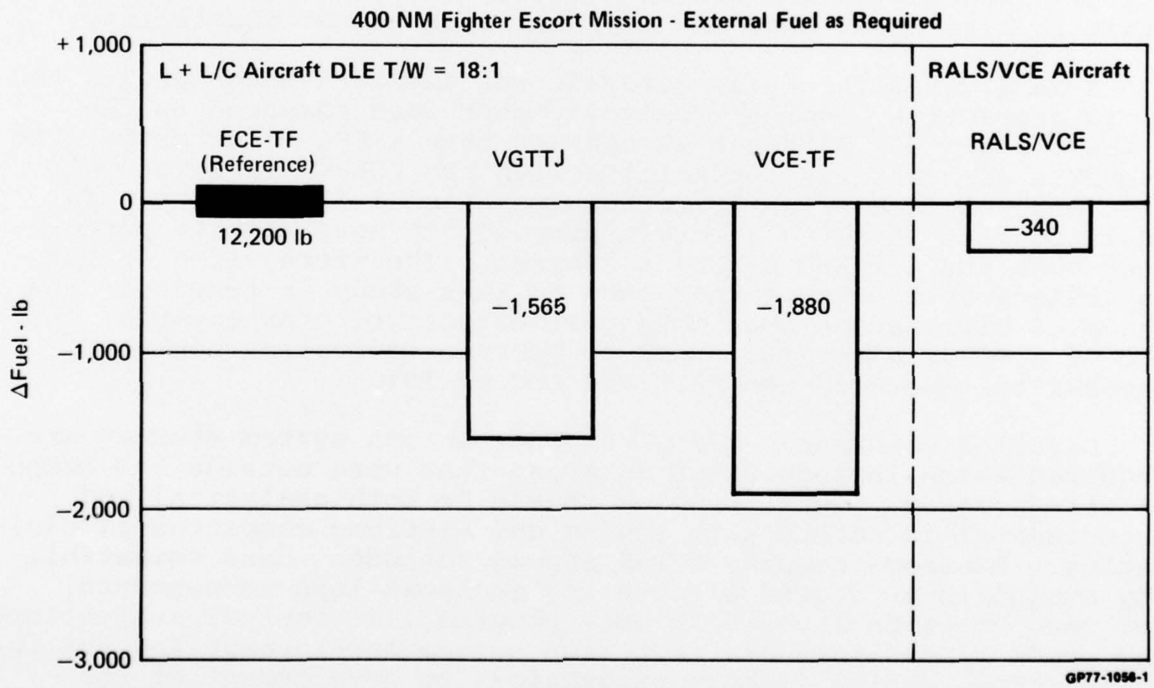

FIGURE 41
VCE PAYOFF ASSESSMENT - OPERATIONAL FLEXIBILITY

6. CONCLUSION & RECOMMENDATIONS

Variable cycle engines have been evaluated using advanced V/STOL fighter designs to assess their payoffs in terms of total weapon system characteristics. Results indicate that they offer potential benefits in supersonic V/STOL fighters. The major conclusions and recommendation are discussed below.

A parametric V/STOL Fighter Design Evaluation Procedure was defined and demonstrated which will be a valuable tool in future V/STOL fighter engine/airframe selections. The procedure accounts for the interactions between requirements and aircraft size, performance and cost. This procedure was used to define a L + L/C fighter data base for conducting design selection and aircraft cost effectiveness trade-offs using fixed cycle turbofan and variable geometry turbine (VGTTJ) engines. VGTTJ aircraft design was defined which had substantial payoffs relative to a fixed cycle turbofan aircraft. These payoffs included a 11% reduction in Intercept mission TOGW, a 9% reduction in life cycle cost and improved operational flexibility.

A V/STOL fighter L + L/C design was also defined using a GE variable cycle turbofan engine (VCE-TF). This engine provided a 9% reduction in Intercept mission TOGW relative to a FCE-TF aircraft. The VCE-TF aircraft was competitive with the FCE-TF aircraft in life cycle cost and improved operational flexibility.

A RALS/VCE lift/cruise aircraft was designed which proved to be an attractive, cost effective concept when compared to the L + L/C designs. Although 4% heavier than a FCE-TF aircraft, the RALS/VCE aircraft was competitive with the FCE-TF in life cycle cost and provided slightly better operational flexibility. In addition, the RALS/VCE aircraft provied 50% more combat performance than the L + L/C aircraft designs. Therefore, if a combat capability greater than that used in this study is required, the RALS/VCE will become even more cost effective. For example, the LCC of a VGTTJ aircraft, sized to provide equivalent combat P_S capability, exceeded the RALS/VCE LCC by 10%.

Detailed supersonic V/STOL fighter weapon system studies are required which include RDT&E in areas that were outside the scope of this program. These studies should be both analytical and experimental in nature with engine and airframe companies participating. Airframe company RDT&E should include: base compatibility evaluations, ground effects and suckdown loss assessments, hot gas ingestion investigations, powered lift control evaluations and primary/auxiliary air induction system development and testing. In addition, engine components critical to development of the modulating bypass VCE-TF concept, including the RALS, should be included in engine company technology demonstrator programs.

Consideration should be given to continuing development of the ADEN nozzle. The capability to augment in the vectored thrust mode increases the allowable STO payload.

At the present time, the Rand TOA model is the only generally acceptable procedure for parametrically predicting engine RDT&E and production cost. New procedures should be developed which reflect the advanced technology impact of variable cycle engines on life cycle costs.

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